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The Clinical Applications of Cone Beam Computed Tomography in Endodontics

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The Clinical Applications of Cone Beam Computed Tomography in Endodontics

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Abstract

A series of 5 investigations assessed the application of cone beam computed tomography (CBCT) for the management of endodontic problems.

Cone beam computed tomography improved the detection of the presence and absence of simulated periapical lesions in human dry mandibles. The overall sensitivity was 0.248 and 1.0 for periapical radiography and CBCT respectively. The receiver operating characteristics (ROC) area under the curve (AUC) values were 0.791 and 1.000 for intraoral radiography and CBCT, respectively.

There was no improvement in the detection of artificially created vertical root fractures (VRF) in root treated teeth using CBCT compared with periapical radiographs. The overall AUC value of incomplete and complete VRF was 0.53 for periapical radiography and 0.45 for CBCT ($p=0.034$). The overall sensitivity of periapical radiography (0.05) was lower than CBCT (0.57) regardless of the extent of the VRF ($p=0.027$). Periapical radiographs (0.98) had a higher overall specificity than CBCT (0.34), ($p=0.027$).

The prevalence of periapical radiolucencies of 273 individual roots in 151 teeth viewed with CBCT (48%) of teeth treatment planned for endodontic treatment was significantly higher when compared with periapical radiographs (20%).

Periapical radiographs and CBCT scans of 123 of the teeth in 99 patients assessed 1 year after completion of primary root canal treatment were compared to their respective pre-treatment periapical radiographs and CBCT scans. Analysis by tooth revealed that the 'healed' rate (absence of periapical radiolucency) was 87% using periapical radiographs and 62.5% using CBCT ($p<0.001$). This increased to 95.1% and 84.7% respectively when the 'healing'

group (reduced size of periapical radiolucency) was included ($p < 0.002$). Outcome diagnosis of teeth showed a statistically significant difference between systems ($p < 0.001$).

The influence of periapical radiography and CBCT for the detection and management of *in-vivo* root resorption lesions was assessed. Periapical radiography ROC AUC values were 0.780 and 0.830 for diagnostic accuracy of internal and external cervical resorption respectively. The CBCT ROC AUC values were 1.000 for both internal and external cervical resorption. There was a significantly higher prevalence ($p = 0.028$) for the correct treatment option being chosen with CBCT compared with intraoral radiographs.

These investigations demonstrated that CBCT is more effective in diagnosis *ex vivo* and *in vivo* periapical radiolucencies, and for the diagnosis and management of root resorption. However, CBCT did not improve the detection of VRF in this experimental model.

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List of abbreviations

AUC	Area under the curve
ALARP	As low as reasonable practicable
CBCT	Cone Beam Computed Tomography
CT	Computed Tomography
MB2	2nd mesio-buccal canal
MRI	Magnetic Resonance Imaging
NPV	Negative Predictive Value
PA	Periapical
PPV	Positive Predictive Value
ROC	Receiver Operating Characteristic
RP	Rapid Prototyping
RPAM	Rapid Prototype Anatomical Models
TACT	Tuned Aperture Computed Tomography
X Ray	Periapical radiograph

Chapter 1

1. Review of the literature.

1.1 Introduction

The management of endodontic problems is reliant on periapical (intraoral) radiographs to assess the anatomy of the tooth under investigation and its surrounding structures (Forsberg 1987a,b, Cotton *et al.* 2009, Patel *et al.* 2009). Radiographic assessment is required at every stage of endodontic treatment; from diagnosis, management and ultimately to assess the outcome endodontic treatment (European Society of Endodontology 2006, Glickman & Pettiette 2006, Wu *et al.* 2009). These radiographs are obtained using radiographic films or digital sensors. However, the images produced have inherent limitations. These include lack of 3-dimensional information, geometric distortion of the area being imaged and the masking of the area of interest by overlying anatomy (anatomic noise).

1.2 Limitations of conventional radiography for endodontic diagnosis

1.2.1 Compression of 3-dimensional anatomy

Radiographs compress 3-dimensional anatomy into a 2-dimensional image or shadowgraph, greatly limiting diagnostic performance (Webber *et al.* 1999, Nance *et al.* 2000, Cohenca *et al.* 2007). Important features of the tooth and its surrounding tissues are visualised in the mesio-distal (proximal) plane only. Similar features presenting in the bucco-lingual plane (i.e. the third dimension) may not be fully appreciated. These include additional roots, root canals and even the quality of root filling (Wu *et al.* 2009).

The spatial relationship of the root(s) to their surrounding anatomical structures and associated periapical lesions cannot always be truly assessed with

conventional radiographs (Cotti *et al.* 1999, Cotti & Campisi 2004). In addition, the location, nature and shape of structures within the root under investigation (for example, root resorption) may be difficult to assess (Cohenca *et al.* 2007, Patel & Dawood 2007, Durack *et al.* 2011). Diagnostic information in this missing 'third dimension' is of particular relevance for the planning of apical surgery (Velvart *et al.* 2001, Low *et al.* 2008, Bornstein *et al.* 2011), where the angulation of the root to the cortical plate, the thickness of the cortical plate and the relationship of the root to adjacent anatomical structures such as the inferior alveolar nerve, mental foramen or maxillary sinus should ideally be appreciated before commencing endodontic surgery.

In an attempt to overcome the limitations of plain radiography, additional exposures with 10-15° changes in horizontal tube head angulation (parallax principle) may be considered (Glickman & Pettiette 2006, Patel & Pitt Ford 2007, Whaites 2007a). Several periapical views taken at different angles may be necessary for diagnosing traumatic dental injuries (for example, root fractures, luxations and avulsion injuries) (Flores *et al.* 2007a,b). Brynolf's classic study found that 3-4 parallax radiographs of the area of interest resulted in a better perception of depth and spatial relationship of periapical lesions associated with root apices (Brynolf 1967). The parallax principle may also separate roots and root canals which are in the same plane as the X-ray beam, for example, allowing identification of the presence of a second mesio-buccal canal in maxillary molars (Manogue *et al.* 2005, Glickman & Pettiette 2006). However, it should be noted that multiple periapical radiographs do not guarantee the identification of all relevant anatomy or disease (Barton *et al.* 2003, Maltherne *et al.* 2008), and may not reveal much more than a single exposure.

The observer's knowledge of the anatomy being assessed and their experience and training in interpreting radiographs taken from different views helps visualise

the area being assessed 3-dimensionally (Nillson *et al.* 2007). However, this mental 3-dimensional picture may not be a true reflection of the anatomy being assessed.

1.2.2 Geometric distortion

Due to the complexity of the maxillo-facial skeleton, radiographic images do not always accurately replicate the anatomy being assessed (Gröndahl & Huuonen 2004). Ideally, radiographs should be taken with a paralleling technique rather than the bisecting technique as it produces more geometrically accurate images (Vande Voorde & Bjorndal 1969, Forsberg & Halse 1994). A series of investigations by Forsberg (1987a,b,c) concluded that the paralleling technique was more accurate than the bisecting angle technique for accurately and consistently reproducing apical anatomy.

For accurate reproduction of anatomy, the image receptor (X-ray film or digital sensor) must be parallel to the long axis of the tooth, and the X-ray beam should be perpendicular to the image receptor and the tooth being assessed. This is usually possible in the mandibular molar region where the floor of the mouth comfortably accommodates the image receptor (Walker & Brown 2005), though there may be compromises in patients with small mouths, gagging predispositions or poor tolerance to the receptor. In the maxilla, a shallow palatal vault may also prevent the ideal positioning of the periapical image receptor even when using a beam-aiming device. This lack of long-axis orientation results in geometric distortion (poor projection geometry) of the radiographic image. The ideal positioning of solid-state digital sensors may be even more challenging due to their rigidity and bulk compared with conventional X-ray films and phosphor plate digital sensors (Wenzel 2006, Whaites 2007a). Over-angulated or under-angulated radiographs (bisecting or paralleling technique) may reduce or increase respectively the radiographic root length of the tooth under investigation

(White & Pharoh 2004, Whaites 2007a), and increase or decrease the size or even result in the disappearance of periapical lesions (Bender & Seltzer 1961a, Bender *et al.* 1966a, Huuonen & Ørstavik 2002).

In ideal conditions, when a 'textbook' paralleling technique radiograph can be exposed, the operator must anticipate a small degree (approximately 5%) of magnification in the final image (Vande Voorde & Bjorndal 1969, Forsberg & Halse 1994). This magnification is caused by the object (i.e. tooth) and the image receptor being slightly separated (more so in the maxilla) and the X-ray beam being slightly divergent. The use of a long focus-to-skin distance may limit, but will not eliminate this magnification (Whaites 2007b).

Positioning the image receptor parallel to the long axis of the tooth may be possible with teeth that have relatively straight roots (for example, incisors and premolar teeth). However, it is not uncommon for multi-rooted teeth to have divergent or convergent root anatomy. In these situations, it is impossible to completely eliminate some degree of geometric distortion and magnification. The net result is that diverging roots will not be displayed accurately in a single exposure due to varying degrees of distortion. This is particularly relevant in the posterior maxilla (Lofthag-Hansen *et al.* 2007).

1.2.3 Anatomical noise

Anatomical features may obscure the area of interest, resulting in difficulty in interpreting radiographic images (Revesz *et al.* 1974, Kundel & Revesz 1976, Gröndahl & Huuonen 2004). These anatomical features are referred to as anatomical, structured or background noise and may be radiopaque (for example, zygomatic buttress), or radiolucent (for example, incisive foramen, maxillary sinus). The more complex the anatomical noise, the greater the reduction in contrast within the area of interest (Morgan 1965, Revesz *et al.* 1974, Kundel &

Revesz 1976) with the result that the radiographic image may be more difficult to interpret (figure 1.1).

The problem of anatomical noise in endodontics was first observed by Brynolf (1967, 1970a), who noted that the projection of the incisive canal over the apices of maxillary incisors may complicate radiographic interpretation. Several studies (Bender & Seltzer 1961a,b, Schwartz & Foster 1971) have concluded that periapical lesions, when confined to the cancellous bone are not easily visualised on radiographs; in these cases the denser overlying cortical plate masks the area of interest. Lee & Messer (1986) suggested that periapical lesions may be successfully detected when confined to cancellous bone, provided the cortical bone was thin and the anatomical noise minimal. Such lesions may go undetected beneath a thicker cortex. Anatomical noise also accounts for some under-estimation of periapical lesion size on radiographic images (Bender & Seltzer 1961a, Schwartz & Foster 1971, Shoha *et al.* 1974, Marmary *et al.* 1999, Scarfe *et al.* 1999).

Paurazas *et al.* (2000) concluded that separately prepared artificial periapical lesions within cortical bone were more accurately detected than equivalent-sized lesions confined to the cancellous bone. There was also an increased likelihood of detecting periapical lesions in both groups (cortical and cancellous bone) as the size of the lesion increased.

The complexity of the anatomy of the maxillary molar region may partially explain why Goldman *et al.* (1972) found that the greatest amount of disagreement between examiners for detecting periapical lesions occurred in this region. It has been suggested that additional radiographs exposed at different angles may be exposed in an attempt to overcome anatomical noise and visualise endodontic lesions more clearly (Huomonen & Ørstavik 2002).



Figure 1.1 A series of radiographs taken with a beam aiming device during the course endodontic treatment of the 12. Note how well defined the existing periapical radiolucency (red arrow) is in the 'pre-endo' radiograph. The periapical radiolucency then appears to become less radiolucent (healing?) in the 'working length' radiograph (yellow arrow). In the 'mid-fill' radiograph the periapical radiolucency (green arrow) becomes more pronounced, and finally returns to the original radiodensity in the 'post-endo' radiograph. The changes in radiodensity of the periapical radiolucency are due to subtle changes in irradiation geometry with each radiograph resulting in variation in the amount of overlying anatomical noise.

Anatomical noise is dependent on several factors, including: overlying anatomy, the thickness of the cancellous bone and cortical plate and finally the relationship of the root apices to the cortical plate. Brynolf (1967) compared the radiographic and histological appearance of 292 maxillary incisor teeth to assess whether there was a relationship between the radiographic and histological features of the periapical lesions. Overall, there was a high correlation between radiographic and histological findings, a conclusion that may have been related to the low anatomical noise in the area being assessed. The root apices of maxillary incisors lie very close to the adjacent cortical plate and therefore erosion of the cortical plate probably occurs very soon after periapical inflammation develops. In other areas of the jaws where there is more anatomical noise (for example, the posterior mandible with its thicker cortical plate), the relationship between histological features and radiographic appearances may be less clear (Pitt Ford 1984).

1.3 Advanced radiographic techniques for endodontic diagnosis

Alternative imaging techniques have been suggested to overcome the limitations of periapical radiographs (Cotti & Campisi 2004, Nair *et al.* 2007, Patel *et al.* 2007). In endodontics, some of these techniques may improve the diagnostic yield and assist clinical management.

1.3.1 Tuned Aperture Computed Tomography (TACT)

Tuned Aperture Computed Tomography works on the basis of tomosynthesis (Webber & Messura 1999). A series of 8-10 radiographic images are exposed at different projection geometries using a programable imaging unit, with specialised software to reconstruct a 3-dimensional data set, which may be viewed slice by slice.

A claimed advantage of TACT over conventional radiographic techniques is that the images produced have less superimposition of anatomical noise over the area of interest (Webber *et al.* 1996, Tyndall *et al.* 1997). The overall radiation dose of TACT is no greater than 1-2 times that of a periapical radiograph as the total exposure dose is divided among the series of exposures taken with TACT (Nair *et al.* 1998, Nance *et al.* 2000). Additional advantages claimed for this technique include the absence of artefacts resulting from radiation interaction with metallic restorations (see later section on computed tomography). The resolution is reported to be comparable to 2-dimensional radiographs (Nair & Nair 2007).

Webber & Messura (1999) compared TACT to conventional radiographic techniques in assessing patients who required minor oral surgery. They concluded that TACT was '*more diagnostically informative and had more impact on potential treatment options than conventional radiographs*'. Nance *et al.*

(2000) compared TACT with conventional film radiography to identify root canals in extracted mandibular and maxillary human molar teeth. With TACT, 36% of second mesio-buccal (MB2) canals were detected in maxillary molar teeth and 80% of third (mesio-lingual) canals were detected in mandibular molars. None of these were detected on conventional X-ray films. The poor results with conventional radiography may have been partly due to the fact that parallax views were not taken. However, Barton *et al.* (2003) concluded that TACT did not significantly improve the detection rate of MB2 canals in maxillary first molar teeth when compared with two conventional radiographs taken using the parallax principle. The detection rate of MB2 canals using either technique was approximately 40%; the true prevalence of MB2 canals was confirmed with the aid of a dental operating microscope to be much higher at 85%. It may be concluded that the complex nature of the adjacent anatomy around posterior maxillary molar teeth limits the use of TACT.

Recently, studies have concluded that TACT is suitable for detecting vertical root fractures (Nair *et al.* 2001, Nair *et al.* 2003). In one of these studies (Nair *et al.* 2001) oblique/vertical root fractures were induced in the mid-third of endodontically treated mandibular single-rooted extracted teeth. These teeth were then radiographed using TACT and conventional digital sensors. It was concluded that the diagnostic accuracy of TACT was superior to 2-dimensional radiography for the detection of vertical root fractures.

Tuned Aperture Computed Tomography appears to be a promising radiographic technique for the future. However, at present it is still only a research tool (Nair & Nair 2007), and has mostly been evaluated *ex vivo*.

1.3.2 Magnetic Resonance Imaging (MRI)

MRI is a specialised imaging technique which does not use ionising radiation. It is based on the behaviour of hydrogen atoms (consisting of one proton and one electron) within a magnetic field which is used to create the MR image. The patient's hydrogen protons normally spin on their axes. The patient is placed within a strong magnetic field, which aligns the protons contained within hydrogen atoms along the long axis of the magnetic field and the patient's body. A pulsed beam of radio waves which has a similar frequency to the patient's spinning hydrogen atoms is then transmitted perpendicular to the magnetic field. This knocks the protons out of alignment, resulting in the hydrogen protons precessing like tiny gyroscopes, moving from a longitudinal to a transverse plane. The atoms behave like several mini bar-magnets, spinning synchronously with each other. This generates a faint radio-signal (resonance) which is detected by the receiver within the scanner. Similar radio-signals are detected as the hydrogen protons relax and return to their original (longitudinal) direction. The receiver information is processed by a computer, and an image is produced (White & Pharoah 2004, Whaites 2007a).

The main dental applications of MRI to date have been the investigation of soft-tissue lesions in salivary glands, investigation of the temporomandibular joint and tumour staging (Goto *et al.* 2007, Whaites 2007b). MRI has also been used for planning dental implant placement (Imamura *et al.* 2004, Monsour & Dhudia 2008). Recently, Tutton & Goddard (2002) performed MRI on a series of patients with dental disease. They were able to differentiate the roots of multi-rooted teeth; smaller branches of the neurovascular bundle could be clearly identified entering apical foramina. The authors also claimed that the nature of periapical lesions could be determined as well as the presence, absence and/or thickening of the cortical bone. Goto *et al.* (2007) compared measurements taken from 3-dimensional reconstructed MRI and computed tomography images of a dry

mandible and hemi-mandible. They concluded that the accuracy of MRI was similar to computed tomography. MRI scans are not affected to the same extent by artefacts caused by metallic restorations (for example, amalgam, metallic extracoronar restorations and implants) which can be a major problem with computed tomography technology (Eggars *et al.* 2005). Cotti & Campisi (2004) suggested that MRI may be useful to assess the nature of endodontic lesions and for planning periapical surgery.

Magnetic Resonance Imaging has several drawbacks including poor resolution compared to simple radiographs and long scanning times. High hardware costs means that access to this type of imaging is only available in dedicated radiology units. Furthermore, specialised training is required to use the hardware and interpret the images. Different types of hard tissue (for example, enamel and dentine) cannot be differentiated from one another or from metallic objects; they all appear radiolucent. It is for these reasons that MRI is of limited use for the management of endodontic disease.

1.3.3 Ultrasound

Ultrasound (US) is based on the reflection (echoes) of ultrasound waves at the interface between tissues which have different acoustic properties (Gundappa *et al.* 2006). Ultrasonic waves are created by the piezoelectric effect within a transducer (probe). The ultrasound beam of energy is emitted and reflected back to the same probe (i.e. the probe acts as both the emitter and detector). The detected echoes are converted by the transducer into an electric signal, from which a real-time black, white and shades of grey echo picture is produced on a computer screen (White & Pharoah 2004). As the probe is moved over the area of interest, a new image is generated. Up to 50 images can be created per second, resulting in moving images on the screen (Cotti *et al.* 2002). The intensity or strength of the detected echoes is dependent on the difference

between the acoustic properties of two adjacent tissues. The greater the difference between tissues, the greater is the difference in the reflected ultrasound energy and the higher the echo intensity. Tissue interfaces which generate a high echo intensity are described as hyperechoic (for example, bone and teeth), whereas anechoic or hypoechoic (for example, cysts) describes areas of tissues which do not reflect or poorly reflect ultrasound energy. Typically, the images seen consist of varying degrees of hyperechoic and anechoic regions as the areas of interest usually have a heterogeneous profile. The Doppler effect (the change of frequency of sound reflected from a moving source) can be used to detect the arterial and venous blood flow (Whaites 2007b).

Cotti *et al.* (2003) used US to assess if it was possible to differentially diagnose periapical lesions. Eleven periapical lesions of endodontic origin were examined with ultrasound imaging. A provisional diagnosis was determined according to the echo picture (hyperechoic and hypoechoic) and evidence of vascularity within the lesion was determined using the colour laser doppler effect. The provisional diagnosis (7 cysts, 4 granulomas) determined by ultrasound was confirmed to be correct histologically in all 11 cases. Gundappa *et al.* (2006), and more recently, Aggarwal *et al.* (2009) also concluded that US was a reliable diagnostic technique for determining the histopathological nature (granuloma versus cysts) of periapical lesions. However, in none of these studies were the apical biopsies removed *in toto* with the root apex (Cotti 2008), therefore making it impossible to confirm whether a cystic appearing lesion was a true or pocket cyst. In addition, the lesions were not serially sectioned making accurate histological diagnosis impossible (Nair *et al.* 1996). The ability of US to assess the true nature and type (for example, true versus pocket cyst) of periapical lesions is doubtful.

Ultrasound is blocked by bone and is therefore useful only for assessing the extent of periapical lesions where there is little or no overlying cortical bone

(Aggarwal *et al.* 2010). While US may be used with relative ease in the anterior region of the mouth, positioning the probe is more difficult against the buccal mucosa of posterior teeth. In addition, the interpretation of US images is most appropriately carried out by radiologists who have had extensive training in examining such images.

Non destructive site-specific evaluation of bone mechanical properties based on non-linear acoustic signals (i.e. highly non-linear solitary waves, HNSW) has been recently proposed (Spadoni & Daraio 2010). Such acoustic signals may improve imaging capabilities through increased accuracy and signal-to-noise ratios. HNSWs are compactly-supported packets of energy, which are generated by a balance of non-linear and dispersive effects in intrinsically non-linear media, such as granular and layered materials. The fundamental understanding of the formation and propagation properties of HNSWs has allowed the development of several engineering applications including shock and impact absorbing layers (Hong 2005, Daraio *et al.* 2006) acoustic lenses (Spadoni & Daraio 2010), and diagnostic scanning devices (Khatri *et al.* 2009), unfortunately clinically suitable devices taking advantage of this principle are not yet available.

1.3.4 Computed tomography

Computed tomography (CT) is an imaging technique which produces 3-dimensional images of an object by taking a series of 2-dimensional sectional X-ray images. Essentially, CT scanners consist of a gantry which contains the rotating X-ray tube head and reciprocal detectors. In the centre of the gantry, there is a circular aperture, through which the patient is advanced. The tube head and reciprocal detectors within the gantry either rotate synchronously around the patient, or the detectors take the form of a continuous ring around the patient and only the X-ray source moves within the detector ring. The data from the detectors produces an attenuation profile of the particular slice of the body being examined.

The patient is then moved slightly further into the gantry for the next slice data to be acquired. The process is repeated until the area of interest has been scanned fully.

Early generations of the CT scanner acquired 'data' in the axial plane by scanning the patient 'slice by slice' using a narrow collimated fan shaped X-ray beam passing through the patient to a single array of reciprocal detectors. The detectors measured the intensity of X-rays emerging from the patient. Over the last three decades, there have been considerable advances in CT technology. Current CT scanners are called multi-slice CT (MSCT) scanners and have a linear array of multiple detectors, allowing 'multiple slices' to be taken simultaneously, as the X-ray source and detectors within the gantry rotate around the patient who is simultaneously advanced through the gantry. This results in faster scan times and therefore a reduced radiation exposure to the patient (Sukovic 2003, White & Pharoah 2004). The slices of data are then 'stacked' and re-formatted to obtain 3-dimensional images and multi-planar images which can be viewed in any plane the operator chooses (for example, axial, coronal or sagittal) without having to expose the patient to further radiation. The interval between each slice may also be varied; closely approximated slices will give better spatial resolution, but will result in an increased radiation dose to the patient.

In addition to 3-dimensional images, CT has several other advantages over conventional radiography. These include the elimination of anatomical noise and high contrast resolution, allowing differentiation of tissues with less than 1% physical density difference to be distinguished compared to a 10% difference in physical density which is required with conventional radiography (White & Pharoah 2004).

CT technology has been applied to the management of endodontic problems. Tachibana & Matsumoto (1990) published one of the first case reports on the application of CT technology in endodontics. They were able to gain additional information on the root canal anatomy and its relationship to vital structures such as the maxillary sinus using reconstructed axial slices and 3-dimensional reconstruction of the CT data. Velvart *et al.* (2001) compared the information derived from CT scans and periapical radiographs of 50 mandibular posterior teeth scheduled for periapical surgery to the clinical findings at the time of surgery. They found that CT could more readily detect periapical radiolucencies and the location of the inferior alveolar nerve compared with periapical radiographs. Furthermore, additional essential information such as the bucco-lingual thickness of the cortical and cancellous bone and the position and inclination of the root within the mandible could only be assessed using CT. They concluded that CT 'should be considered before the surgical treatment of mandibular premolars and molars when on the dental radiograph the mandibular canal is not visible or in close proximity to the lesion/root'.

An *in vivo* study compared the detection of periapical lesions at 7, 15, 30 and 60 days after bacterial contamination of dogs' teeth and concluded that CT was able to detect the presence of periapical lesions which were not readily detectable on periapical radiographs (Jorge *et al.* 2008). After 7 days 32.5% of periapical lesions were detected with CT; none of these lesions were identified with periapical radiographs, this increased to 83.3% and 47.4% respectively after 15 days.

Huumonen *et al.* (2006) assessed the diagnostic value of CT and parallax periapical radiographs of maxillary molar teeth requiring endodontic re-treatment. More periapical lesions were detected with CT compared with periapical radiographs. In addition, the distance between the palatal and buccal cortical plates and the root apices could only be determined with CT. Huumonen *et al.*

(2006) concluded that the information obtained from CT was essential for decision making in surgical re-treatment, for example, whether to approach the palatal root palatally or buccally. A recent case series report suggested that the combined use of CT and US may be helpful in the diagnosis and non-surgical management of periapical lesions (Aggarwal & Singla 2010). However, one should bear in mind that a very high radiation dose is required to achieve a high enough resolution to assess root canal anatomy in adequate detail with CT.

CT may also be useful for the diagnosis of poorly localised odontogenic pain. In these circumstances, conventional radiographs of the periapical tissues may not reveal anything untoward. In these cases CT may confirm the presence of a periapical lesion (Velvart *et al.* 2001). The assessment of the 'third dimension' with CT imaging also allows the number of roots and root canals to be determined, as well as where root canals join or divide. This knowledge is extremely useful when diagnosing and managing failing endodontic treatments. Huumonen *et al.* (2006) found that CT detected 30 of the 39 endodontically treated maxillary molars had 2 mesio-buccal canals, 27 of these were unfilled of which 22 had periapical lesions.

The uptake of CT in endodontics has been slow for several reasons, including the high effective dose and relatively low resolution of this imaging technique. Other disadvantages of CT are the high costs of the scans, scatter due to metallic objects, poor resolution compared with conventional radiographs and the fact that these machines are only found in dedicated radiography units (for example, hospitals, imaging centres). Access may thus be problematic for dentists in practice. CT technology has now become superseded by Cone Beam Computed Tomography technology in the management of endodontic problems.

1.4 Cone Beam Computed Tomography

1.4.1 Technological aspects

Cone beam computed tomography (CBCT) or digital volume tomography (DVT) was developed in the late 1990's to produce 3-dimensional scans of the maxillo-facial skeleton at a considerably lower radiation dose than conventional computed tomography (CT) (Mozzo *et al.* 1998, Arai *et al.* 1999). In 2006 there were only 5 CBCT scanners available in the market; to date (January 2012) there are over 25 different CBCT scanners available.

With CBCT a 3-dimensional volume of data is acquired in the course of a single sweep of the extraoral X-ray source and reciprocal sensor which synchronously rotate through 180° to 360° around the patient's head depending on the scanner used and/or the exposure parameters selected (figure 1.2a). The X-ray beam is cone-shaped (hence the name of the technique), and captures a cylindrical or spherical volume of data, described as the field of view (FOV). The size of the field of view is variable. Large volume CBCT scanners (for example, i-CAT®, [Imaging Sciences International, Hatfield, PA, USA] & NewTom 3G®, [QR, Verona, Italy]) are capable of capturing the entire cranio-facial skeleton. Some CBCT scanners also allow the height of the cylindrical FOV to be adjusted to capture the entire maxillofacial region, maxilla or mandible (e.g. i-CAT). This has the advantage of reducing the patient radiation dose. Limited volume CBCT scanners (for example, the 3D Accuitomo®, [J Morita Corporation, Osaka, Japan]) can capture a smaller FOV 40mm high by 40mm diameter volume of data, which is similar in overall height and width to a periapical radiograph. The size of the field of view (FOV) is primarily dictated by the beam projection geometry, collimation and the size and shape of the reciprocal detector (Loubele *et al.* 2009). Other benefits of a smaller FOV are that the reconstruction times are shorter and the resolution is higher than larger FOV scans (Scarfe *et al.* 2009).

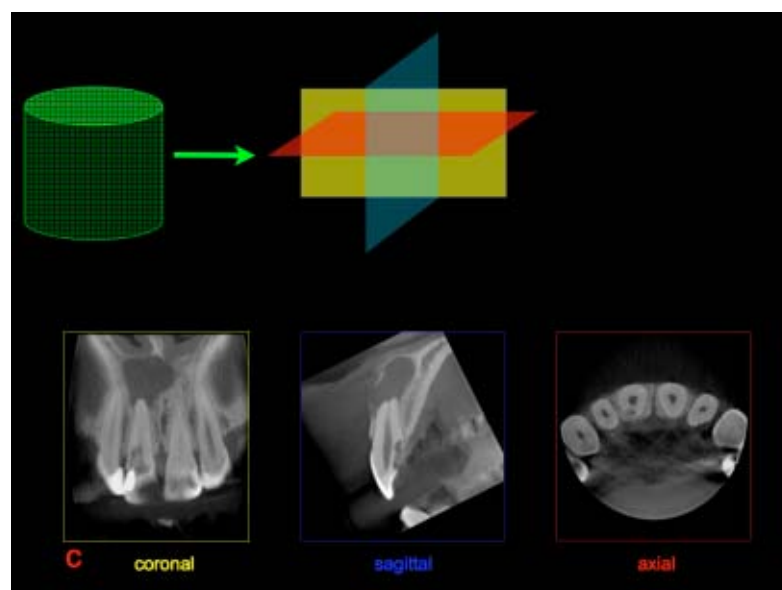
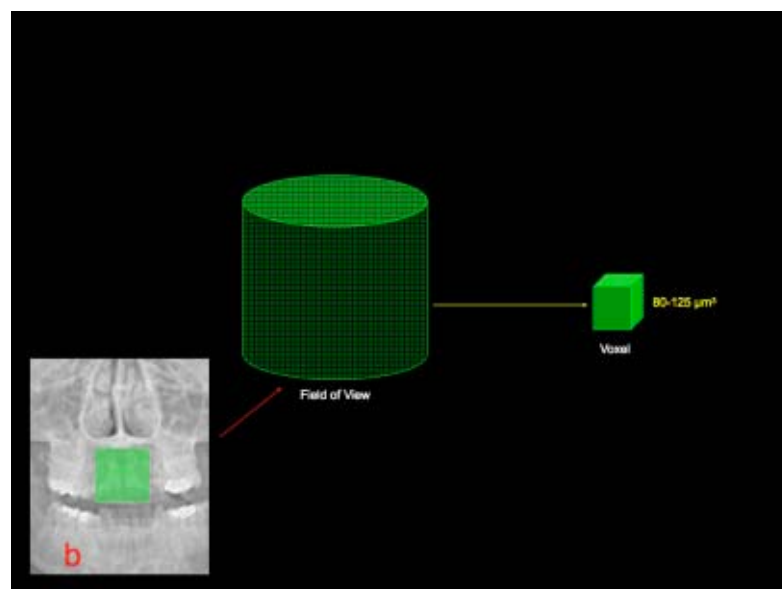
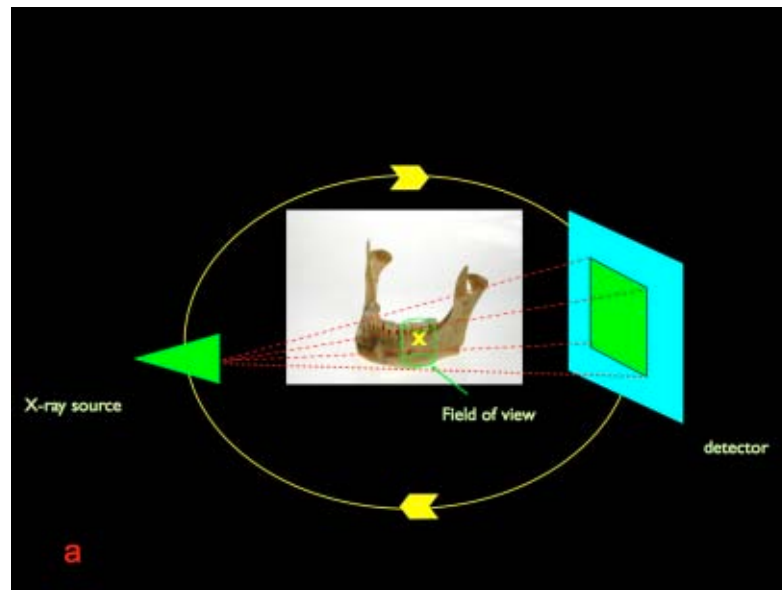
CBCT scan times are typically between 10-40 seconds, depending on the scanner used and the exposure parameters selected. The actual exposure time is a fraction of the scanning time (2-5 seconds) as during the exposure sequence up to 580 individual 'mini-exposures' or 'projection images' are taken. This contrasts with the continuous exposure of CT and conventional tomography and affords the major advantage over CT scanners of substantially reduced radiation exposure.

Sophisticated software processes the collected data into a format that closely resembles that produced by medical CT scanners (figure 1.2b). Each mini-exposure or projection image generates a pixel matrix consisting of 262,144 (512×512) pixels. The resulting dataset from CBCT consists of up to 580 individual matrices which are then reconstructed using powerful personal computers into 3-dimensional data sets, consisting of over 100 million voxels (512^3). Reconstruction is achieved in just minutes. To increase resolution, the number of pixels per matrix (projection image) may be increased from 512^2 to 1024^2 pixels. The resulting reconstructed 3-dimensional volume of data will then consist of 1024^3 voxels, each voxel being half its original size. However, this improved resolution comes at the expense of a two- to three-fold increase in radiation exposure (Scarfe & Farman 2008).

Reconstructed CBCT images may be displayed in a number of different ways (figure 1.2c-d). One option is for the images to be displayed in the 3 orthogonal planes (axial, sagittal and coronal) simultaneously, allowing the clinician to gain a truly 3-dimensional view of the area of interest. Selecting and moving the cursor on one image simultaneously alters the other reconstructed slices, thus allowing the area of interest to be dynamically traversed in 'real time'. For the first time, clinicians are not constrained by these predetermined views; multiplanar

reconstructions are possible which allow virtually any view to be selected. Software allows the window levels to be adjusted and areas of interest to be magnified. Surface rendering using software programmes is also possible to produce truly 3-dimensional images. The image quality of CBCT scans is superior to helical CT for assessing the cancellous bone, periodontal ligament, lamina dura, enamel, dentine and pulp (Hashimoto *et al.* 2003, 2007).

CBCT scanners use simpler, less complicated and therefore less expensive hardware (X-ray source and detector) than CT scanners, and employ powerful, low cost computers (Baba *et al.* 2004, Cotton *et al.* 2007). Therefore the cost of a CBCT scanner is significantly less than a CT scanner. In addition the overall footprint of CBCT scanners is similar or slightly larger than a panoramic machine. These factors have resulted in an increase in its uptake in dental practices (Arnheiter *et al.* 2006, Scarfe *et al.* 2006, Patel *et al.* 2010). The majority of scanners scan the patient sitting down, however, CBCT scanners exist which either scan the patient sitting up or lying down; the latter has the disadvantage of taking up more space, and also may be less accessible to patients with disabilities.



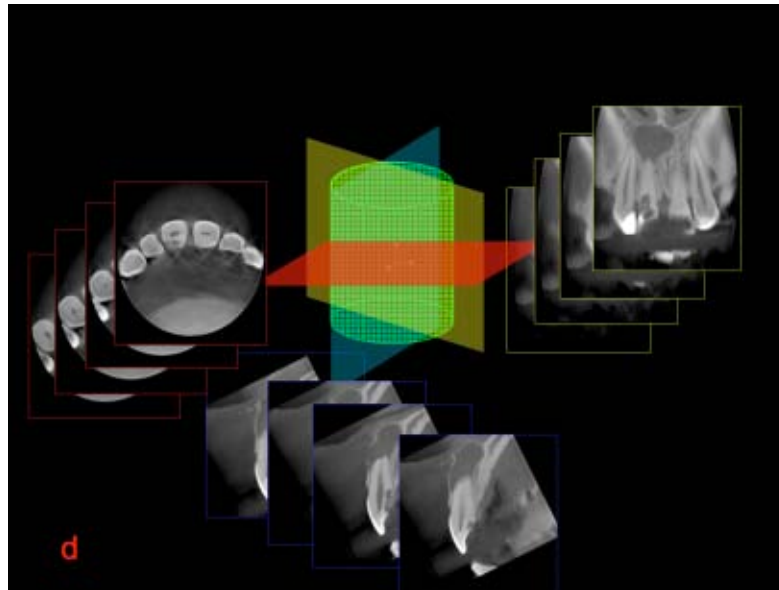


Figure 1.2 (a) A cone-shaped X-ray beam and the detector rotate once around the patient and captures a cylindrical volume of data (field of view), (b) the collected data within the field of view is collated as voxels, therefore a typical field of view consists of millions of voxels. Software is used to reconstruct images for this dataset. (c) Typically cross-sectional images in three orthogonal views are generated from the cone beam computed tomography scan, (d) the clinician selects the position and thickness of the slice selected from within cylindrical or spherical volume of data. The three views can be assessed simultaneously, traversing through one plane simultaneously alters the other two planes.

1.4.2 Effective dose

There are three basic dose units in radiation dosimetry. These are: the *radiation absorbed dose* (D), the *equivalent dose* (H) and the *effective dose* (E). The *radiation absorbed dose* is defined as the measure of the amount of energy absorbed from the radiation beam per unit mass of tissue and is measured in joules/kg. The unit used to compare different absorbed dosages is the Gray (Gy). It cannot be used to compare the dose from one investigation to another because it does not allow for how dangerous the type of radiation might be, nor does it allow for the sensitivity of the particular part of the body that is being irradiated. To achieve this comparability, various mathematical calculations are performed and the other dose units are used. The *equivalent dose* is defined as a measure that indicates the radiobiological effectiveness of different types of radiation and

thus provides a common unit. It is calculated by multiplying the radiation absorbed dose by the radiation quality weighting factor. The radiation weighting factor (W_R) for X rays is 1. The radiation quality weighting factor is a figure which describes the damaging nature of different types of radiation. It is also measured in joules/kg, but the unit used to compare different equivalent doses is the Sievert (Sv). A second mathematical calculation can now be performed to take into account the part of the body that is irradiated. This results in the *effective dose*, which is calculated by multiplying the equivalent dose by different tissue weighting factors which converts all doses to an equivalent whole body dose. This allows doses from different investigations of different parts of the body to be compared to each other and to the natural background radiation dose. The unit remains as the Sievert (Sv) and can be used to estimate the damage from radiation to an exposed population.

One of the major advantages of CBCT over CT is the significantly lower effective radiation dose to which patients are exposed (table 1). The X-ray source of CBCT provides a more focused X-ray beam and less radiation scatter compared with CT (Sukovic 2003). The CBCT radiation dose depends on several factors; these include the size of the FOV, whether the X-ray beam is continuous or pulsatile, the number of basis images, the exposure parameters (mA, kV and scanning time), the beam filtration and the voxel size settings. The effective dose of CBCT scanners vary, but can be almost as low as a panoramic dental radiograph and considerably less than a medical CT scan (Ngan *et al.* 2001, Ludlow *et al.* 2006, Lofthag-Hansen *et al.* 2008). As would be expected, the limited volume scanners which are specifically designed to capture information from a small region of the maxilla or mandible deliver a lower effective dose as less of the maxillo-facial skeleton is being exposed to radiation (table 1.1). The limited volume CBCT scanners are therefore best suited for endodontic imaging of only one or two neighbouring teeth. Indeed, the effective dose of one CBCT

scanner (3D Accuitomo) has been reported to be in the same order of magnitude as 2-3 standard periapical radiographic exposures (Arai *et al.* 2001). Recently, Loubele *et al.* (2009) assessed the effective dosages of a series of CBCT scanners. The effective dosages varied from 13 to 82 μ Sv, depending on the scanner used and the exposure parameters. The CBCT scanners used in the research presented in this thesis were Veraviewpocs® and Accuitomo 3D®, (J Morita Corporation). According to Loubele *et al.* depending on the area being scanned with the 3D Accuitomo, the effective dose varied from 13 μ Sv (mandibular anterior region) to 44 μ Sv (maxillary canine and premolar region). As the Veraviewpocs® has a 180° arc of rotation compared to a full 360° arc of rotation with the 3D Accuitomo®, the effective dosages are potentially even lower (7-22 μ Sv).

There is now evidence to suggest that adjusting the exposure parameters away from the manufacturer's default settings by using 180° rotation rather than a full 360° rotation can result in CBCT images which are still of diagnostic use but at a significantly lower (half) radiation dose (Durack *et al.* 2011, Lennon *et al.* 2011). These *ex vivo* studies should now ideally be validated *in vivo*.

It is essential that the radiation dose is kept *As Low as Reasonably Achievable* (ALARA) when exposing patients to ionizing radiation (Farman 2005, IRMER 2000). Therefore, each radiation exposure must be *justified*, after which the radiographic view, and therefore the patient radiation dose must be *optimized*. The smallest FOV compatible with the clinical situation should be prescribed, as this will result in a lower radiation dose (Patel & Horner 2009). Optimisation is especially important in children and adolescent patients (table 1.2), who are more sensitive to the stochastic effects of radiation (Verdun *et al.* 2008, Qu *et al.* 2010, Theodorakou *et al.* 2011).

Radiographic source	Effective dose (μSv)	% annual background radiation dose
Periapical	5	0.14
Panoramic	6.3	0.2
CT (mandible)	1320	39
3D Accuitomo® (small FOV)	13-44	1
i-CAT® (large FOV)	64	2

Table 1.1 Effective dosages and background radiation dosages from different radiographic sources, (adapted from Patel *et al.* 2009, Loubele *et al.* 2009).

Age group (years)	Multiplication factor for risk
<10	x3
10-20	x2
20-30	x1.5
30-50	x0.5
50-80	x0.3
80+	Negligible risk

Table 1.2 Risk in relation to age (Adapted from Selection Criteria for Dental Radiography, Royal College of Dental Practitioners 2004).

1.4.3 Accuracy of reproduction

CT and CBCT data are composed of a huge volume of data consisting of millions of 3-dimensional pixels called voxels. However, this is where the similarities end. CT voxels are anisotropic and the height of the voxel depends on the CT beam (slice) thickness, which limits the accuracy of reconstructed images in certain planes (for example sagittal plane). With CBCT data the voxels are isotropic, i.e. they are equal in length, height and depth, which allow geometrically accurate measurements from CBCT data in any plane (Kobayashi *et al.* 2006, Scarfe *et al.* 2006, Cotton *et al.* 2007).

Several studies have confirmed the 3-dimensional geometric accuracy of CBCT (Kobayashi *et al.* 2004, Murmulla *et al.* 2005, Ludlow *et al.* 2007, Mischkowski *et al.* 2007, Stratemann *et al.* 2008). Lascala *et al.* (2004) took a series of 13 measurements from 8 dry skulls before they were scanned and measured using CBCT software. CBCT was found to be extremely accurate. Al-Ekrish & Ekram (2011) found that CBCT was more accurate than CT for measuring the distance between 2 landmarks (gutta-percha markers) in human jaws. Ludlow *et al.* (2007) concluded that CBCT gave accurate 2- and 3-dimensional measurements regardless of skull orientation. They also concluded that CBCT was reliable for taking linear measurements of the maxillo-facial skeleton. Obenauer *et al.* (2007) has confirmed accurate volumetric analysis with CBCT, a feature which could potentially be useful in the objective monitoring of periapical lesion size.

Pinsky *et al.* (2006) created simulated osseous defects of varying diameters and depths in an acrylic block and a human mandible. These authors found that accurate linear and volumetric measurements of the simulated defects could be acquired using CBCT software to automatically measure the volume of the defect. Michetti *et al.* (2010) concluded that there was a 'strong correlation' between 3-dimensional reconstructions of the root canal outlines of extracted teeth to their corresponding histological sections.

An *in vivo* study carried out on dog's teeth compared the assessment of periapical healing using CBCT and periapical radiographs with histological analysis being used as the reference standard (Paula-Silva *et al.* 2009a). It was found that CBCT evaluation of lamina dura disruption and the signs of external inflammatory resorption closely corresponded to the histological picture.

1.4.4 Limitations of CBCT

At present the images produced with CBCT technology do not have the resolution of conventional radiographs. The spatial resolution of conventional direct-action packet film and digital sensors is in the order of 15-20 line pairs mm^{-1} (Farman & Farman 2005). CBCT images only have a spatial resolution of 2-6 line pairs/mm (Yamamoto *et al.* 2003, Scarfe *et al.* 2009). However, as CBCT technology improves at a rapid rate, so may the resolution of the reconstructed scans. The higher resolution scanners are especially relevant in endodontics. However, better resolution comes at the expense of increased radiation to the patient.

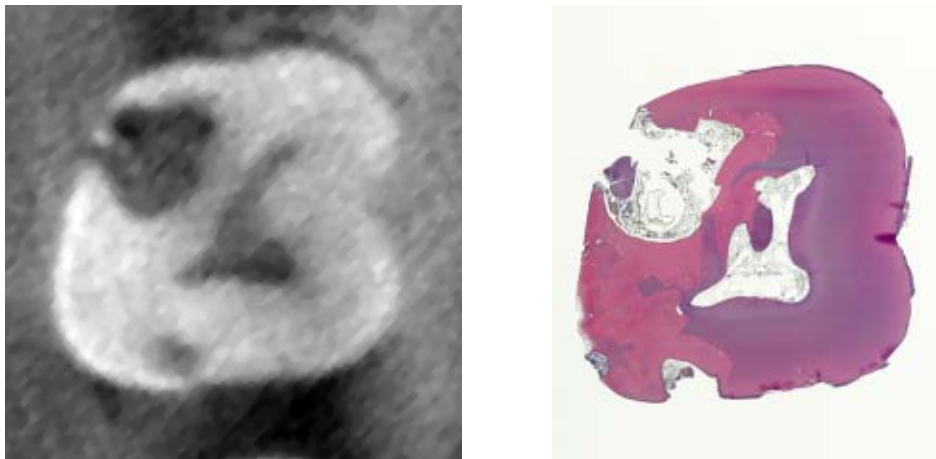


Figure 1.3 (left) Axial slice of a mandibular molar with external cervical resorption, (right) histological slice of matched axial slice of the tooth. Note how the metaplastic bone can be clearly differentiated from dentine histologically, but cannot be detected on the CBCT slice. This is due to the poor contrast resolution with CBCT. Histology prepared by D Riccuci.

CBCT has poor contrast resolution, and therefore tissues of similar radiodensities are not readily discernible (figure 1.3). This is due to several factors which include image noise due to radiation scatter, low mA, divergence of the X-ray beam (heel-effect) and imperfections in the detector (Scarfe *et al.* 2009).

As the whole of the FOV is irradiated with each basis image, scatter is produced in all directions (figure 1.4). This results in 'noise' or graininess in the resulting

images, which is also known as 'image noise'. This can be reduced by increasing the mAs, and if the CBCT scanner allows, by increasing the number of basis images and therefore the exposure time.

Another significant problem which can affect the image quality and diagnostic accuracy of CBCT images are artefacts (Scarfe & Farman 2008). It has been reported that this can be due to several factors which include the patient (i.e. movement during the scan), the CBCT system (under-sampling, partial volume averaging, the cone beam effect) and beam hardening (Akdeniz *et al.* 2006, Mora *et al.* 2007, Soğur *et al.* 2007). Scatter and beam hardening is typically caused by high density neighbouring structures such as enamel, metal posts, root canal filling materials and restorations. If this scattering and beam hardening occurs close to, or is associated with the tooth being assessed, the resulting CBCT images may lose diagnostic value (Lothag-Hansen *et al.* 2007, Estrela *et al.* 2008, Bueno *et al.* 2010). In some instances this may lead to an incorrect diagnosis (Krithikadatta *et al.* 2010).

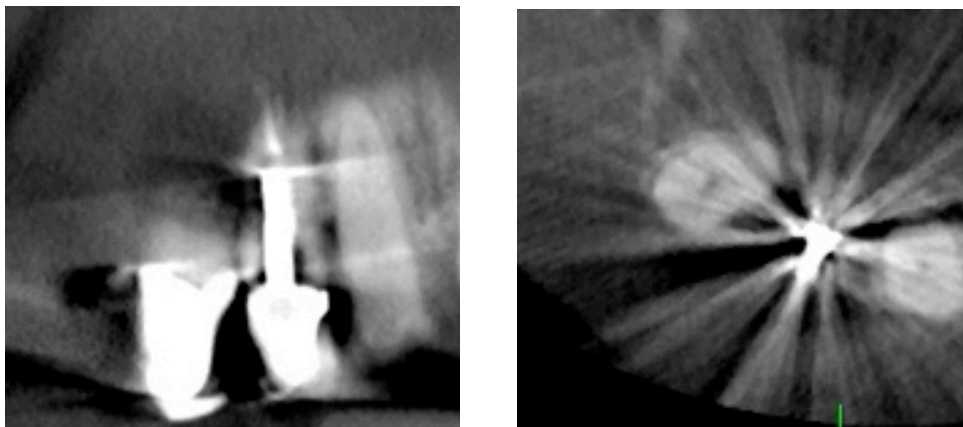


Figure 1.4 (left) coronal, and (right) axial reconstructed slices demonstrating the scatter caused by high atomic structure objects such as gold intra-canal posts.

CBCT technology is improving quickly; manufacturers have now introduced algorithms to reduce artefacts due to noise, metal and patient movement.

However, this comes at the expense of increased reconstruction times (Scarfe & Farman 2008).

1.4.5 Three-dimensional modelling

CBCT data can also be used to produce physical models, a process commonly known as Rapid Prototyping (RP). True scale models (Rapid Prototype Anatomical Models [RPAMs]) can be produced of the area of interest using 3-dimensional printing techniques such as stereolithography or selective laser sintering (Lal *et al.* 2006, Dawood *et al.* 2008). The ability to produce 3-dimensional rendered images and an exact model using RP of the area of interest from the CBCT scans means that the operator can tangibly familiarise themselves with the potential surgical site and confidently plan their surgical approach (Patel *et al.* 2007, 2009, Keightley *et al.* 2010).

1.5 The use of CBCT in the management of endodontic problems

CBCT overcomes several limitations of conventional radiography. Slices can be selected to avoid adjacent anatomical noise. For example, the roots of maxillary posterior teeth and their periapical tissues can be visualised separately and in all 3 orthogonal planes without superimposition of the overlying zygomatic buttress, alveolar bone and adjacent roots. The spatial relationship of the roots of multi-rooted teeth can be visualised in 3-dimensions (Soğur *et al.* 2007), and the true size and 3-dimensional nature of periapical lesions can also be assessed (Cotton *et al.* 2007, Patel *et al.* 2007).

1.5.1 Detection of apical periodontitis

CBCT enables radiolucent periapical radiolucencies to be detected before they would be apparent on conventional radiographs (Paula-Silva *et al.* 2009a,b). Lofthag-Hansen *et al.* (2007) published one of the first studies to compare the

prevalence of periapical lesion detection of periapical radiographs and CBCT. They assessed the periapical status of 46 posterior mandibular and maxillary teeth using CBCT scans and two angled (parallax) periapical radiographs. Thirty-two teeth were diagnosed with periapical lesions using conventional radiographs, and a further 10 (31%) with CBCT. When the periapical status of the individual roots of these teeth was assessed, CBCT allowed 62% more periapical lesions to be detected than with conventional radiographs. This was especially apparent in the mandibular and maxillary second molar region, and was probably due to a combination of selecting relevant CBCT data without adjacent anatomical noise and the geometric accuracy of the CBCT scanner. Similar findings have been reported in other studies (Low *et al.* 2008, Bornstein *et al.* 2011).

Estrela *et al.* (2008a) compared the ability of panoramic and periapical radiography and CBCT to detect radiographic signs of periapical periodontitis associated with 1508 untreated, and endodontically treated teeth in 888 consecutive patients with a history of endodontic problems. The prevalence of periapical periodontitis was 18%, 35% and 63% with panoramic, periapical and CBCT, respectively. Their results confirmed the increased sensitivity of CBCT for detecting periapical periodontitis compared with periapical and panoramic radiography. The sensitivity of periapical and panoramic radiography was 0.55 and 0.28, respectively.

These clinical studies presumed that the radiological findings from CBCT represent the true status of the periapical tissues, i.e. that CBCT can be presumed to be the 'reference standard' with a sensitivity and specificity of 1.0 in the detection of periapical disease.

The results of these clinical studies have been validated by *ex vivo* experiments in which periapical lesions have been intentionally created, i.e. the periapical

status is known beforehand. Stavropolous & Wenzel (2007) compared the ability of CBCT and digital and conventional periapical radiography to detect artificially created periapical lesions of varying sizes in pig mandibles. CBCT was found to be twice as sensitive as digital and conventional radiography. *Ex vivo* studies using human jaws have also found CBCT to be more accurate than periapical radiographs for assessing the presence or absence of periapical lesions (Özen *et al.* 2009, Sogur *et al.* 2009).

Estrela *et al.* (2008b) examined the periapical status of 1014 endodontically treated teeth in 596 patients. Radiographic signs of apical periodontitis were seen in 39.5% of teeth assessed with periapical radiography; the prevalence of apical periodontitis increased to 60.9% when the same teeth were assessed with CBCT. Conventional radiographs appear to under-estimate the prevalence of periapical disease.

Paula-Silva *et al.* (2009b), in a well designed animal study using histology as the reference standard, reaffirmed that CBCT was a more accurate diagnostic tool than conventional radiography for diagnosing periapical periodontitis. In this *in vivo* study, 83 roots were examined histologically after root canal treatment was carried out using single and two-visit root canal treatments on teeth with radiological signs of periapical periodontitis; there was also a vital group, and a control group of teeth with periapical periodontitis which were left untreated, but histologically examined. At the 6 month follow up the animals were sacrificed and the roots with the surrounding periapical bone were histologically examined. As would be expected the specificity and Positive Predictive Value (PPV) of radiographs and CBCT were 1, i.e. perfect accuracy for correctly determining the absence of periapical disease. However, the sensitivity of CBCT (0.91) was much higher than periapical radiography (0.77). This was also reflected in the Negative Predictive Values (NPV) for CBCT and periapical radiographs, which were 0.46

and 0.25 respectively. The overall accuracy of CBCT and radiographs in the diagnosis of periapical periodontitis was 0.92 and 0.78 respectively.

The radiographic outcome of root canal treatment is better when teeth are treated before obvious radiographic signs of periapical disease are detected (Friedman 2002). Thus, earlier identification of periapical radiolucent changes with CBCT may result in earlier diagnosis and more effective management of endodontic disease. In situations where patients have poorly localised symptoms associated with an untreated, or previously root treated tooth, and clinical and periapical radiographic examination show no evidence of disease, CBCT may reveal the presence of previously undiagnosed pathoses (Nakata *et al.* 2006, Cotton *et al.* 2007, Pigg *et al.* 2011).

Simon *et al.* (2006) compared the ability of CBCT grey scale value measurements with histological examination for diagnosing large periapical lesions in 17 teeth. They suggested that by using CBCT they were able to differentiate 'solid from cystic or cavity type lesions' which they claimed would improve decision making when it came to deciding to carry out surgery. However, all the lesions were not completely intact and no attempt was made to carry out serial sectioning of the biopsy material, which meant that it was not possible to accurately confirm the type of lesion present.

Due to the limitations of conventional radiography, it does appear that the size of periapical lesions is under-estimated when compared to CBCT (Christiansen *et al.* 2009, Paula Silva *et al.* 2009c).

The current evidence suggests that CBCT does have a higher sensitivity compared with periapical radiography for the detection of periapical lesions. The specificity of both types of imaging systems is similar. It has been suggested that

CBCT may be indicated in cases where patients are symptomatic but clinical and conventional radiographic imaging is unremarkable (Patel 2009, SedentexCT 2011).

1.5.2 Pre-surgical assessment

CBCT has been recommended for the planning of endodontic surgery (Tsurumachi & Honda 2007). Rigolone *et al.* (2003) concluded that CBCT may play an important role in planning for periapical microsurgery on the palatal roots of maxillary first molars. The distance between the cortical plate and the palatal root apex could be measured, and the presence or absence of the maxillary sinus between the roots could be assessed. CBCT imaging allows the anatomical relationship of the root apices to important neighbouring anatomical structures such as the inferior dental canal, mental foramen and maxillary sinus, to be clearly identified in any plane the clinician wishes to view (Patel *et al.* 2007, Lofthag-Hansen *et al.* 2007, Bornstein *et al.* 2011). CBCT images may result in avoiding periapical surgery of maxillary molar teeth where the floor of the sinus has been perforated by a larger than estimated periapical lesion which may have not been readily detected on periapical radiographs (Maillet *et al.* 2011).

By selecting relevant CBCT images, the thickness of the cortical plate, the cancellous bone pattern, the presence and position of fenestrations, as well as the inclination of the roots of teeth planned for surgery can be accurately determined preoperatively (Nakata *et al.* 2006, Lofthag-Hansen *et al.* 2007, Low *et al.* 2008). Root morphology and bony topography can be visualised in 3-dimensions, as can the number of root canals and whether they converge or diverge from each other; this information is essential to improve the outcome of treatment. Unidentified (and untreated) root canals may be identified using axial slices which may not be readily identifiable with periapical radiographs (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008) The true size, location and extent of the

periapical lesion can also be appreciated, while the actual root with which the lesion is associated may be confirmed. This information may have a bearing on non-surgical and surgical management.

Recently, Low *et al.* (2008) compared the findings of periapical radiographs with those of CBCT in root treated maxillary posterior teeth which were being assessed for periapical surgery. In this study 34% of periapical lesions detected by CBCT were not detected with periapical radiographs. The likelihood of detecting periapical lesions with periapical radiographs was reduced when the root apices were in close proximity to the floor of the maxillary sinus, and when there was less than 1mm of bone between the periapical lesion and the sinus floor. Therefore, periapical radiographs were less sensitive for detecting periapical lesions associated with maxillary molar teeth. Bornstein *et al.* (2011) carried out a similar study on root treated mandibular posterior teeth and had similar results; 26% of periapical lesions were missed by periapical radiographs.

1.5.3 Assessment of dental trauma

CBCT has been shown to be useful in diagnosis and management of dento-alveolar trauma (Cohenca *et al.* 2007a, Cotton *et al.* 2007, Tsukiboshi 2008). The exact nature and severity of alveolar and luxation injuries can be assessed from just one CBCT scan from which several views may be selected and assessed with no geometric distortion or anatomical noise. It has been reported that CBCT images can be used to detect horizontal root fractures (Terakado *et al.* 2000). The same fracture may have needed multiple periapical radiographs taken at several different angles to be confirmed, and even then may not have been visualised. As CBCT is an extraoral technique it is also far more comfortable for the patient who has recently sustained dental trauma when compared to several periapical radiographs taken using a paralleling device. Cohenca *et al.* (2007a) used CBCT to aid their management of 3 patients who had sustained dental

trauma. In addition to detecting the true nature of the injuries sustained by the tooth, the CBCT scans were able to detect cortical bone fractures which were not diagnosed from the clinical or conventional radiographic examination.

Kamburoğlu *et al.* (2009) found that despite the analysis of periapical radiographs taken at 3 different angles, CBCT was far more sensitive for detecting the presence of horizontal root fractures. The nature (for example, the location and angulation) of the root fractures assessed with CBCT images differs from conventional imaging techniques, this may have an impact on the management and ultimately the prognosis of root fractured teeth (Bornstein *et al.* 2009). CBCT has also been shown to be an effective tool for the diagnosis of alveolar fractures of the maxillofacial skeleton which may otherwise be difficult to accurately diagnose on plain film radiographs (Dölekoğlu *et al.* 2009, Shintaku *et al.* 2010).

External inflammatory resorption, is a common sequela of dental trauma (Andreasen & Hjørting-Hansen 1966a,b, Andreasen & Vestergaard-Pedersen 1985). The diagnosis is solely based on radiographic signs (Andreasen *et al.* 1987). It is well documented that early diagnosis of this process is not reliable with conventional radiographs (Andreasen *et al.* 1987, Chapnik 1989, Goldberg *et al.* 1998). CBCT has been found to be more diagnostically accurate for detecting the early signs of external inflammatory resorption when compared with periapical radiographs (Durack *et al.* 2011). This study compared the accuracy of digital radiographs and CBCT for the assessment of simulated external inflammatory resorption lesions in dry mandibles and concluded that CBCT was more accurate and reliable at diagnosing these lesions at an early stage. An assessment of the presence and nature of inflammatory root resorption on 48 teeth with a history of trauma or orthodontic treatment was carried out by Estrela *et al.* (2009). Radiographic signs of inflammatory root resorption were assessed on the coronal, mid-, and apical-thirds of the root. Inflammatory root resorption

was detected on a 154 surfaces when assessed with CBCT, compared to 83 surfaces when assessed with periapical radiographs. In addition, periapical radiographs appeared to underestimate the depth of the resorption lesions, with 95.8% of lesions extending more than 1mm into the root being detected with CBCT compared with only 52.1% with periapical radiographs.

It has also been demonstrated that reducing arc of rotation from 360° to 180°, thereby approximately halving the effective dose, did not have an impact on the diagnostic value of the CBCT images (Durack *et al.* 2011).

1.5.4 Assessment of root canal anatomy

Anatomical variations exist with each type of tooth (Vertucci 1984, Kulild & Peters 1990). The 2-dimensional nature of radiographs means that they do not consistently reveal the actual number of canals present in teeth (Tu *et al.* 2007, Patel 2009, Zheng *et al.* 2010). This may potentially lead to inability to identify all the roots present, potentially resulting in incomplete disinfection of the root canal system which may ultimately lead to a poorer outcome of endodontic treatment (Wolcott *et al.* 2005).

Matherne *et al.* (2008) conducted an *ex vivo* investigation to compare charged-couple device and photostimulable phosphor plate digital radiography systems with CBCT to detect the number of root canals in 72 extracted mandibular incisors, first premolars and maxillary first molar teeth. They found that with digital radiographs, regardless of the system used, endodontists failed to identify at least one root canal in 40% of teeth despite taking parallax radiographs compared with CBCT. However, among the drawbacks of this study were the fact that a radiologist and endodontists assessed the CBCT scans and the digital radiographs respectively, and a scanner (i-CAT) without the capability of taking

small FOVs was used. Finally, the teeth were not sectioned to confirm the true number of root canals compared with the 'gold standard' CBCT data.

A series of Taiwanese studies assessed the prevalence of disto-lingual roots in mandibular first molar teeth assessed with conventional radiographs and CBCT; they found that the prevalence of disto-lingual canals was 21% and 33% respectively, with radiographs and CBCT respectively (Tu *et al.* 2007, Tu *et al.* 2009).

In another study, using large FOV scans taken with an i-CAT scanner, extracted maxillary first and second molar teeth were assessed for the prevalence of second mesio-buccal (MB2) canals (Blattner *et al.* 2010). After scanning, the teeth were sectioned axially and the true number of canals present was determined. There was an 80% correlation between the CBCT findings and the clinical sectioning. Intra-examiner agreement with CBCT was 90%, indicating an excellent level of reliability. Neelakantan *et al.* (2010) analysed 95 teeth with small volume CBCT, CT, peripheral quantitative CT, plain and contrast medium enhanced digital radiography. The prevalence of canals from each of these imaging systems was compared to the reference standard of staining and clearing of the teeth. CBCT was found to be as accurate as the reference standard, and the accuracy of CT was in the same order of magnitude. Interestingly, the CT was not as accurate as CBCT. This may have been because these images were found to be more challenging to assess by endodontists. As with previous studies, the inter- and intra-examiner agreement was significantly higher with CBCT (and the other 3D imaging systems) when compared with parallax radiographs.

Zheng *et al.* (2010) looked at CBCT scans of 701 Chinese subjects to specifically assess the root canal morphology of maxillary first molar teeth. They found the

highest number of additional canals in younger patients (20-30 years), and the prevalence of additional canals declined in older groups. One possible reason for canals not being identified is the fact that with increasing age canals become sclerosed, and therefore potentially more difficult to detect due to the poor resolution and contrast of CBCT. Filho *et al.* (2009) concluded that the use of a dental operating microscope and CBCT leads to an increased likelihood of canals being located. Canal curvatures in the bucco-lingual may also be detected which may otherwise only be estimated by negotiation of the root canal system. Estrela *et al.* (2008c) used CBCT to determine the radius of curvature of root canals, and concluded that CBCT is a reliable tool to confidently and accurately assess the severity of the radius of curvature of root canals. This information is essential to minimise aberrations in curved root canals and/or instrument separation.

In addition to being useful for assessing the root canal anatomy of teeth with 'typical anatomy', CBCT is particularly useful for assessing the teeth with known complex anatomy, such as dens invaginatus and fused teeth (Patel 2010, Song *et al.* 2010, Durack & Patel 2011).

CBCT is a useful addition to the endodontist's armamentarium and has been shown to improve the detection rate of root canals when compared to conventional radiographs (Matherne *et al.* 2008, Filho *et al.* 2009). Prior knowledge of the number of root canals, and their location not only results in predictable identification of all the root canal entrances, but also has the advantage of minimising the size of the access cavity (Tu *et al.* 2009, Patel 2010). Logically, the improved detection of root canals should mean that more of the complex root canal is accessed, disinfected and obturated, which should in turn improve the outcome of endodontic treatment. However, it must be remembered that due to the poor resolution of CBCT, sclerosed and/or accessory anatomy may not be readily identified.

1.5.5 Diagnosis and management of root resorption

Even with the use of parallax radiographic techniques the identification and correct differentiation of internal and external cervical resorption may be challenging (Gulabivala & Searson 1995, Kamburoğlu *et al.* 2008). CBCT images have been successfully used in the diagnosis and management of resorptive lesions (Patel & Dawood 2007). CBCT is able to reveal the true nature and exact location of the lesion, determine the 'portal of entry' of the resorptive lesion and also reveal previously undetected resorptive lesions (Cohenca *et al.* 2007b, Patel & Dawood 2007, Nakata *et al.* 2009). With this additional information, decision making on treatment strategies may be more predictable. For example, CBCT slices may reveal if an external cervical resorptive lesion has perforated the root canal or if an internal resorptive lesion has perforated into the adjacent periradicular tissues; this information is crucial for treatment planning.

Kamburoğlu *et al.* (2011) compared the ability of 3 examiners to detect artificially created internal and external cervical lesions. Three parallax periapical radiographs were compared to CBCT images. They concluded that CBCT had a superior accuracy to periapical radiographs. In addition, intra-observer and inter-observer agreement was also higher with CBCT, indicating that this radiographic system was a more reliable and reproducible imaging system.

1.5.6 Assessment of root filled teeth

In clinical practice radiological assessment of the endodontically treated root canal system is necessary to assess the quality of endodontic treatment (Soğur *et al.* 2007, Moura *et al.* 2009). The homogeneity, quality and length of the root canal filling material within the root canal system is a helpful outcome predictor of endodontic treatment (Sjögren *et al.* 1997, Huybrechts *et al.* 2009). Theoretically, voids within the root canal filling may potentially adversely affect the outcome of endodontic treatment as these spaces may allow existing bacteria to proliferate

and/or act as avenues of bacterial leakage. An ideal root canal filling would be a void-free, homogenous mass sealing the entire root canal system.

The ability of CBCT and periapical radiographs to detect voids of varying sizes has been addressed in an *ex vivo* investigation by Huybrechts *et al.* (2009). They concluded that small voids within root fillings were not detected by CBCT when compared to digital imaging receptors. Interestingly, they also found that analogue receptors (X-ray film) was ineffective at detecting small voids (<350µm) compared with digital image receptor systems. This may be due to the fact the E speed films were used, rather than D speed film with smaller halide particles. Wu *et al.* (2009) found that the mesio-distal (clinical) view consistently underestimated the presence of voids when compared to the perpendicular bucco-lingual (non-clinical) view of the mesial root of mandibular molars. This may be a result of the superimposition of the buccal root over the lingual root, coupled with the fact that the dimensions of these canals is wider in the bucco-lingual (non-clinical) plane (Wu *et al.* 2000, Mannocci *et al.* 2005). Thus an apparently good quality root filling assessed by conventional radiography does not necessarily reflect the actual quality of the root filling (Kersten *et al.* 1987, Wu *et al.* 2009).

The superiority of CBCT over periapical radiographs for assessing root canal filling length has recently been highlighted in a study by Moura *et al.* (2009). In this study the influence of root canal filling length on radiological signs of apical periodontitis was assessed. With radiographs, the proportion of root canal filling length 1-2mm short of the radiological apex of anterior, premolar and molar teeth was 88%, 89% and 95% respectively. When the same teeth were assessed with CBCT, the proportion of root canal filling length 1-2mm short of the radiological apex was far lower at 70%, 74% and 79%, respectively. This over-estimation of the end-point of root canal fillings assessed by periapical radiographs was most probably due to a combination of geometrical distortion and the 2-dimensional

nature of conventional radiographs. As the CBCT dataset can be reformatted, teeth may be positioned so that each root of a multi-rooted tooth can be individually assessed in the clinical and non-clinical views with minimal distortion. Liang *et al.* (2011) radiographically assessed the outcome of endodontic treatment of 143 roots in 115 teeth using periapical radiographs and CBCT. In 73% of cases there was agreement between the two radiographic systems in determining the apical extent of the root fillings. However, with periapical radiographs 80% (20 of the 25) of 'short' fillings were actually 'flush' when assessed with CBCT, and 31% of root fillings judged to be 'flush' with periapical radiographs were actually 'long' when assessed with CBCT. This study also found that voids were under-estimated with periapical radiographs (16%), when compared to CBCT (46%).

The limitations of CBCT for assessing root canal fillings was highlighted by Soğur *et al.* (2007) who compared film and digital periapical radiographs to small volume CBCT for the ability to assess the homogeneity and length of root canal fillings. A 3 point scale was used to grade the root fillings and CBCT was found to be inferior to film and digital based radiography for assessment of both length and homogeneity. The presence of streaking artefacts adversely affected the quality of the image produced with CBCT. The low mA and the use of an image intensifier in this study may also have contributed to the increased noise in the poor quality CBCT images. Less noise, and therefore better quality images, may now be possible with the use of the latest generation flat panel detector, and more suitable exposure parameters. A recent case report by Krithikadatta *et al.* (2010) highlighted the problems of scatter from root fillings. In their case report, scatter from an adjacent obturated root canal was mistaken for an additional canal which resulted in additional unnecessary treatment being carried out.

1.5.7 Diagnosis of vertical root fractures

The clinical and radiographic diagnosis of vertical (longitudinal) root fractures is often challenging (Tamse *et al.* 1999, Rivera & Walton 2009, Hassan *et al.* 2010). Typical signs of a vertical root fracture include narrow isolated periodontal probing depths on either side of the tooth, multiple sinuses, and a halo or 'J' shaped radiolucency (Pitts & Natkin 1983, Tamse *et al.* 2006). However, these clinical and radiographic signs may not be associated with incipient root fractures or even long-standing fractures.

The fracture has to lie in the plane of the X-ray beam for it to be visualised radiographically, usually it is the radiographic signs of bone loss around the root with a suspected root fracture that results in a clinical diagnosis (Tamse *et al.* 1999, Fuss *et al.* 2001). Due to the superimposition of overlying anatomy and the 2-dimensional nature of radiographs these root fractures are not consistently diagnosable with conventional radiography, even with the use of parallax views (Hassan *et al.* 2009a).

Periapical radiographs and CBCT have been used to assess vertical root fractures *ex vivo* (Hassan *et al.* 2009, Hassan *et al.* 2010, Özer 2011). These studies do appear to confirm that CBCT is more sensitive at detecting the presence of a root fracture when compared to periapical radiographs. However, the presence of a root filling material does reduce the specificity of CBCT due to the root filling material creating star-shaped streaking artefacts (Hassan *et al.* 2009) which may be mistaken for fracture lines. The diagnostic accuracy of CBCT in the assessment of root fractures does appear to vary depending on the scanner used, which in turn may be due to the variation in exposure and reconstruction parameters used (Hassan *et al.* 2010b).

1.5.8 Assessment of the outcome of endodontic treatment.

Perhaps the most exciting area in which CBCT may be applied to in endodontics is in determining the outcome of treatment. CBCT scans should result in a more objective and accurate determination of the prognosis of endodontic treatment (Liang *et al.* 2011 Patel *et al.* 2011, Wesselink *et al.* 2011).

Paula-Silva *et al.* (2009b) compared the outcome of endodontic treatment in dogs using periapical radiographs and CBCT. The roots of 96 dog's premolar and molar teeth were assessed after vital pulpectomy, single visit and 2 visit endodontic treatment on teeth with radiographic signs of preoperative periapical periodontitis. Six months after endodontic treatment a favourable outcome was detected in 79% of teeth assessed with a periapical radiograph, but was only 35% when CBCT was used; a 44% difference. Interestingly, the results of this study appeared to show that poorer outcome was reached with single visit endodontic treatment when compared with multiple visit endodontic treatment. This research group also found that the size of periapical lesions was consistently under-estimated by periapical radiographs (Paula-Silva *et al.* 2009c).

Liang *et al.* (2011) compared the outcome of endodontic treatment after 2 years with periapical radiographs and CBCT. They found that a favourable outcome was reached in 87% of cases assessed with periapical radiographs and 74% of cases assessed with CBCT images; a 13% difference. The smaller difference may have been due to the fact that none of the teeth had pre-operative periapical radiolucencies when assessed by periapical radiographs.

Future research may show that periapical tissues which appear to have 'healed' on conventional radiographs may still have signs of periapical disease (for example, widened periodontal ligament space, periapical radiolucency) when imaged using CBCT. This in turn may have implications for decision making and

selection criteria when considering (re-) placing coronal restorations on teeth which have previously been endodontically treated and appear to have successfully healed radiographically (Faculty of General Dental Practitioners UK, 2004). Different outcome predictors may be revealed when assessing outcome with CBCT and this may help us understand the healing dynamics of endodontically treated teeth as well as revealing different outcome predictors (Wu *et al.* 2011).

1.6 Conclusion

CBCT technology is improving at a rapid pace; at the same time more companies are introducing CBCT scanners into a steadily increasing and competitive market. This should result in a reduction in the cost of CBCT scanners, which in turn will increase their uptake with dentists. Users of CBCT must be adequately trained in CBCT radiology as well as interpretation of these images as they are completely different to conventional radiography systems. CBCT data captures a considerable amount of data. This is especially so with large volume scans even when the FOV has been reduced. All the data on the scan and not just the area of interest must be examined and any anomalies must be reported and acted upon by the dental surgeon requesting the scan or by a specialist radiologist (Scarfe *et al.* 2006, Nair *et al.* 2007).

It is essential to remember that CBCT uses ionizing radiation, and therefore is not without risk. It is essential that patient radiation exposure is kept as low as reasonably practicable (ALARP) and that evidence-based selection criteria for CBCT use are developed. The benefits of a CBCT investigation must outweigh any potential risks (Farman 2005, Vandenberghe *et al.* 2007). Therefore endodontic cases should be judged individually, and until further evidence is available CBCT should only be considered in situations where information from

alternative imaging systems does not yield an adequate amount of information to allow appropriate management of the endodontic problem.

CBCT overcomes many of the limitations of periapical radiography. The increased diagnostic data should result in more accurate diagnosis and therefore improved decision making for the management of complex endodontic problems. It is a desirable addition to the endodontist's armamentarium and its use should be incorporated into endodontic postgraduate programs.

When indicated, 3-dimensional CBCT scans may supplement conventional '2-dimensional' radiographic techniques, which at present have higher resolution than CBCT images. In this way the benefits each system may be harnessed (Vandenberghe *et al.* 2007).

Chapter 2

2. The detection of simulated periapical lesions in human jaws using CBCT and periapical radiography.

2.1 Introduction

Chronic apical periodontitis is the localised inflammation of the periapical tissues caused by bacterial infection from within the root canal system and the surrounding dentine (Huomonen & Ørstavik 2002, Nair 2004). It can present radiographically as a periapical radiolucency which is due to a localised inflammatory reaction to infection within the root canal system reducing the mineral density of the adjacent affected periapical bone (Bender 1982, Ørstavik & Larheim 2008). The ability of radiographic systems to detect signs of chronic apical periodontitis is essential in Endodontology for diagnosis, treatment planning, determination of outcome and epidemiological studies (Bender 1982, Ørstavik & Larheim 2008, Patel *et al.* 2009a). At present periapical radiography is the technique of choice for diagnosing, managing and assessing endodontic disease (Lofthag-Hansen *et al.* 2007, Nair & Nair 2007), but it is well established that periapical radiography is of limited use for detecting chronic apical periodontitis (Huomonen & Ørstavik 2002).

Anatomical features (noise) immediately adjacent to the area of interest may result in poor contrast and therefore increased difficulty in assessing the periapical tissues. Several studies (Bender & Seltzer 1961, Pauls & Trott 1966, Schwartz & Foster 1971) have concluded that artificially created periapical lesions in posterior region of dry jaws are not easily visualised on radiographs when confined to the cancellous bone (the area of interest), as they are masked by the more mineralised and therefore denser overlying cortical bone (i.e. the anatomical noise). Periapical lesions are usually only diagnosed when there has been perforation or erosion of the overlying cortical plate. Lee & Messer (1986)

suggested that periapical lesions, which have been successfully detected when confined to the cancellous bone, may not be readily observed if the thickness of the cortical bone is increased, i.e. the anatomical noise increases resulting in less contrast between the area of interest (periapical lesion in cancellous bone) and overlying anatomical noise (cortical bone). Regan & Mitchell (1963) came to similar conclusions after assessing the radiological findings of 289 teeth in 27 human cadavers.

The cortical plate, which acts as anatomical noise, is also one of the reasons why the size of a periapical lesion is under-estimated when compared to the actual size of the periapical lesion (Schwartz & Foster 1971, Shoha *et al.* 1974, Paula-Silva *et al.* 2009c). Another factor which may influence the size of a periapical radiolucency is the inability to position beam aiming devices correctly in certain situations. This can cause geometric distortion that may result in an increase or decrease in the size of the periapical lesion, or even result in the inability to visualise periapical lesions (Bender & Seltzer 1961, Huuonen & Ørstavik 2004).

As described in chapter 1, Tachibana & Matsumoto (1990) were among the first to recognise the benefits of computed tomography in endodontics. Computed tomography has been used in the management of endodontic problems to overcome the limitations (anatomical noise and geometric distortion) of conventional radiography (Marmary *et al.* 1999, Velvart *et al.* 1999). CT has now been superseded by CBCT for hard tissue imaging of the maxillo-facial skeleton (Scarfe *et al.* 2009). Small FOV CBCT scanners have a smaller field of view (3-4cm³), and are ideal for 3 dimensional imaging in endodontics (Cotton *et al.* 2007).

Lofthag-Hansen *et al.* (2007) compared CBCT scans with two-angled (parallax) periapical radiographs to assess the periapical status of posterior mandibular and

maxillary teeth. The prevalence of periapical radiolucencies associated with teeth with endodontic problems was 31% higher when CBCT was used. Estrela *et al.* (2008) compared the ability of panoramic and periapical radiographs with CBCT for the radiographic signs of apical periodontitis. Their results confirmed the apparent increased sensitivity of CBCT for detecting apical periodontitis. Similar findings have also been reported by Low *et al.* (2008). These clinical studies appear to assume that the radiological findings from CBCT represent the true status of the periapical tissues, i.e. that CBCT can be used as a 'gold standard' to detect the presence or absence of periapical disease (lesions). The captured CBCT data may also reveal additional relevant information about root canal morphology and neighbouring anatomical structures (for example, the maxillary sinus, mandibular nerve), the true nature and relationship of a periapical lesion to a root and the thickness of the cortical and cancellous plates (Low *et al.* 2008), which cannot be readily obtained from conventional radiological views .

The aim of the present study was to compare the diagnostic accuracy of CBCT with that of periapical radiography for the detection of artificially prepared periapical bone defects in dry human jaws.

2.2 Materials and Methods

2.2.1 Subject material

Ten first molar teeth in 6 partially dentate intact human dry mandibles were used this study (Department of Anatomy and Human Sciences, King's College London, University of London). Each mandible was soaked for 90 minutes in warm water into which hand dish washing liquid (Fairy Liquid Original, Procter & Gamble, Weybridge, Surrey, UK) had been added to reduce the surface tension of the bone therefore increasing its water absorption. This increased the moisture content and the resilience of the dry mandibles for the subsequent extraction of

the teeth. Screening radiographs and CBCT scans were taken of each first molar tooth to identify existing periapical lesions.

Prosthetic dental wax (Ribbon Wax, Metrodent, Huddersfield, UK) was used as a soft tissue substitute. The wax was applied in layers. Periapical radiographs and CBCT scans (refer to 2.2.2 radiographic technique) were taken after each incremental layer of wax had been applied and compared to equivalent *in vivo* views. The process was continued until the radiological appearance of the dry mandible was similar to the radiological appearance of patient's mandibular molars. Once the optimal thickness of wax had been determined it was applied to all mandibles.

The crown of the first molar tooth was sectioned through the furcation separating the mesial and distal roots. The distal root was then a traumatically extracted (figure 2.1). The base of the socket was inspected with the aid of a dental operating microscope (3 step entrée Dental Microscope, Global, St. Louis, MO, USA) to confirm that it was intact. The root was then firmly replaced into the socket. Baseline periapical radiographs and CBCT scans were taken. Four first molar teeth were not used (1 had an existing periapical lesion and 3 were fractured as they were being extracted).

The distal root was then removed again and a spherical periapical lesion of 2 mm (small) in diameter was prepared by drilling a hole into the cancellous bone at the base of the extraction socket using a pre-measured dental laboratory bur (No. 406702 Diadur® Carbide Cutter. Bracon, Etchingham, UK) in a laboratory handpiece. The mandible was then soaked in warm soapy water again for 15 minutes and the root was then firmly reimplanted into its socket. Periapical radiographs and CBCT scans were then taken. The process was repeated using a second bur to enlarge the existing periapical lesion to 4mm (large) in diameter

(No. 406602 Diadur® Carbide Cutter. Bracon). A fresh fillet of beef tightly wrapped in cling film was used to mimic the tongue in the mandible for CBCT scans.

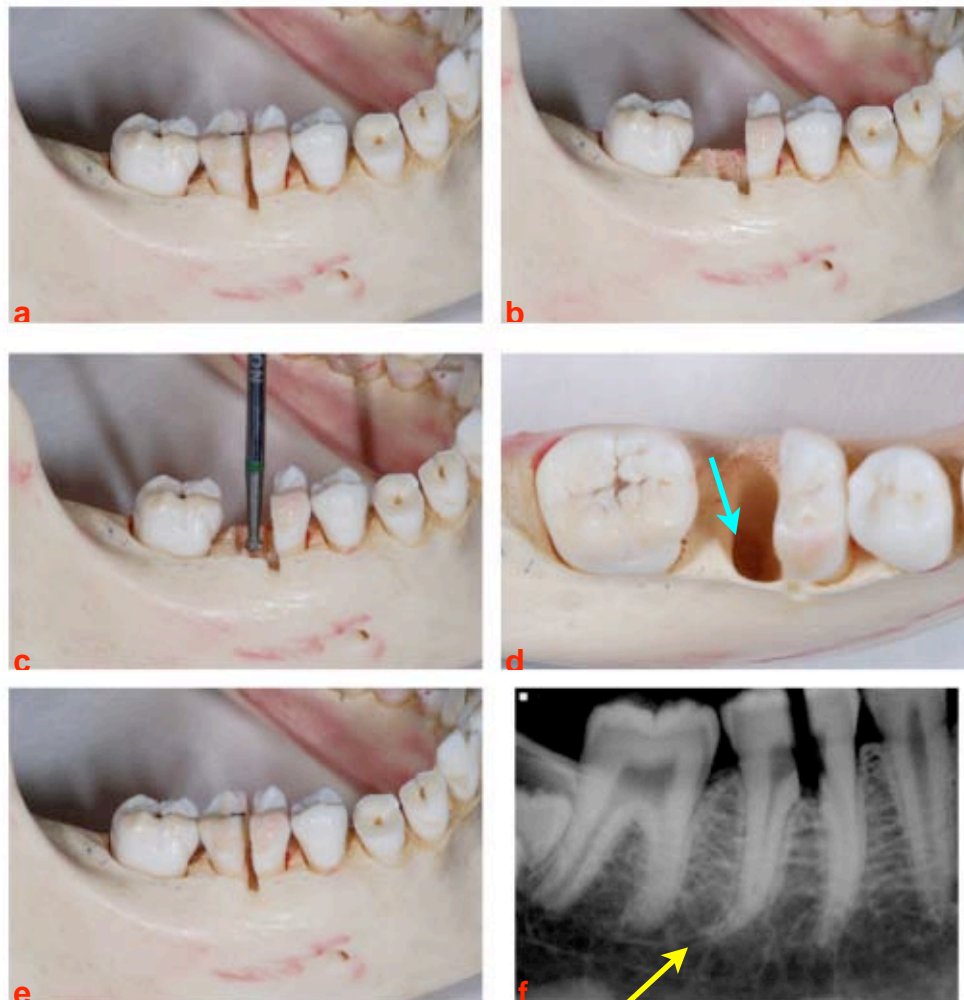


Figure 2.1. (a) Dry mandible* with lower right first molar sectioned through furcation, (b) distal root has been sectioned and a traumatically extracted, (c) laboratory bur inserted into socket to prepare a periapical lesion in the cancellous bone, (d) periapical lesion prepared (turquoise arrow), (e) distal root inserted back into the socket, (f) post-operative radiograph confirms that a periapical radiolucency cannot be seen (yellow arrow). * ribbon wax was removed before taking photographs 2.1a-e.

2.2.2 Radiographic technique

Two jigs were made for each mandible, one to allow standardised reproducible radiographs to be taken with a dental X-ray machine (Planmeca Prostyle Intra, Helsinki, Finland) using a digital CCD (Schick Technologies. New York, NY, USA).

A second jig was made for standardised images to be taken with the small volume CBCT scanner (Veraviewpocs®, J Morita). The angle (i.e. the border between the ramus and body) of each mandible was embedded in polyvinylsiloxane impression material (President, Coltène AG, Altstätten Switzerland) mounted onto MDF board using cyanoacrylate adhesive (SuperGlue, The Original Super Glue Corporation, Rancho Cucamonga, CA, USA). Once set, each mandible could be removed and reinserted in exactly the same position into its own jig. The X-ray tube head and digital sensor were also secured into position using a similar technique. The X-ray tube head, digital sensor and mandible were aligned to allow radiographs to be exposed using the paralleling technique. A similar jig was made for each mandible to be exactly repositioned in the CBCT scanner. Exposure parameters of 66kV, 7.5mA and a 0.10 second were used for the periapical radiograph, and 80 kV, 3.0 mA and a 17.5 second scan for the CBCT scanner. CBCT data was reformatted to align the root axis with the vertical plane in the sagittal and coronal views. The brightness and contrast of all the acquired CBCT images was enhanced to improve visualisation of the periapical lesions. All CBCT data was reformatted (0.125 slice intervals and 1.5 mm slice thicknesses).

2.2.3 Radiological assessment

Six examiners (endodontists n=2, endodontic postgraduates n=4) individually assessed the radiographs and CBCT images in the following sequence: session 1 - radiographs (including duplication to assess intra-observer agreement), session 2 - CBCT images, session 3 - CBCT images repeated (to assess intra-observer agreement).

The images were randomly ordered in each session and viewed as a Power Point® presentation (Microsoft, Seattle, WA, USA) on a laptop computer (Toshiba Portege R500-11Z, Tokyo, Japan) which had a screen pixel resolution of 1280 x

1024. A CBCT image that best confirmed the presence or absence of a radiolucent periapical lesion in the sagittal and coronal planes was chosen by the author as the starting point for each tooth observation. Examiners also had access to the raw CBCT data allowing them to scroll through any of the orthogonal scans. All images were assessed in a quiet dimly lit room. The examiners were trained using examples of clinical radiographs and CBCT images with and without the presence of periapical lesions before embarking on the assessment; a periapical lesion was defined as a radiolucency associated with the radiographic apex of the distal root of the mandibular first molar, which was at least twice the width of the periodontal ligament space (figures 2.2 & 2.3).

Examiners were asked to note down the presence or absence of a periapical lesion using a 5 point confidence scale as follows: 1 - periapical lesion definitely not present, 2 - periapical lesion probably not present, 3 - unsure, 4 - periapical lesion probably present, 5 - periapical lesion definitely present.

There was at least a one week interval between each session. To assess intra-examiner validity for the radiographic assessment 9 radiographs were repeated within session 1. Session 3 was used to assess intra-examiner validity for session 2. Images were displayed in a randomised sequence in each session.

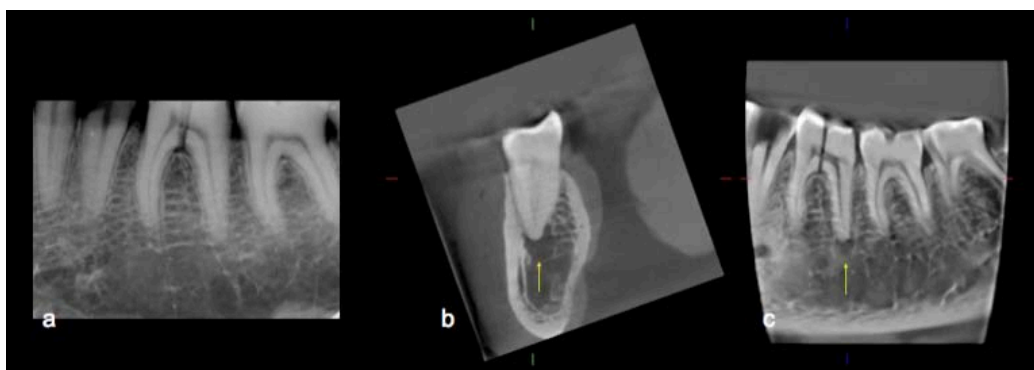


Figure 2.2. (a) Periapical radiograph, and (b) coronal and (c) sagittal reconstructed CBCT images of the same region of interest. Note that the artificial lesion (yellow arrows) can be identified on the CBCT images but not on the periapical radiograph.

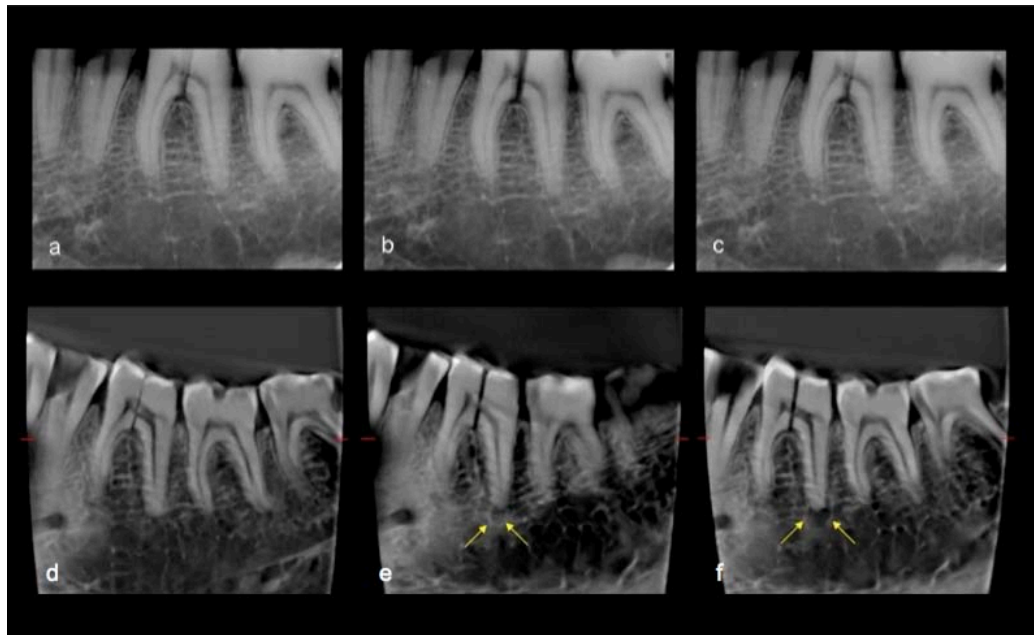


Figure 2.3. Top row radiographs (a-c), bottom row reconstructed sagittal CBCT images of a lower left first molar tooth (d-f). (a) Periapical radiograph where no periapical lesion has been created in the dry mandible, (b) 2mm periapical lesion created, (c) 4mm periapical lesion created directly below the distal root socket.-no radiolucency is apparent in figure 2.3b or c. Note how the artificial periapical lesions (indicated by the yellow arrows) are clearly present on the CBCT images (e-f).

2.2.4 Data analysis

Stata™ software (Stata 9, College Station, Texas, USA) was used to analyse the raw data.

Sensitivity, specificity and predictive values were determined; Receiver Operating Characteristic (ROC) curve analysis was used to assess the diagnostic accuracy (area under the curve [AUC]) of each examiner, and each imaging system for detecting the presence or absence of a periapical lesion. Individual p values for each examiner were inherent in the ROC analysis.

Inter-examiner and intra-examiner agreement was assessed by Kappa statistics for 50% of the periapical radiographs and 100% of the CBCT scans.

Comparison between periapical radiographs and CBCT for all variables was performed using the Wilcoxon matched-pairs, signed-ranks test on results for the six examiners. Statistical significance was inferred where $p < 0.05$.

2.3 Results

The overall sensitivity of periapical radiography (0.248) was lower than CBCT (1.000) regardless of the size of the lesion ($p=0.026$), i.e. these techniques correctly identified all periapical lesions in 24.8% and 100% of cases respectively. Both imaging techniques had high specificity values of 1.000, i.e. both techniques were equally accurate in diagnosing healthy periapical periodontium (table 2.1-2.3). The sensitivity of periapical radiography was lower than CBCT for detecting the presence of both 'small' periapical lesions (0.200; $p=0.014$) and 'large' periapical lesions (0.350; $p=0.024$).

The ROC analysis for periapical radiography revealed a lower (area under the curve) AUC value (0.766) than CBCT (1.000) for the detection of smaller periapical lesions ($p=0.028$). The ROC curves can be found in Appendix I. Similarly, the periapical radiography AUC value (0.860) for the detection of larger periapical lesions was also less than that for CBCT (1.000) ($p=0.027$). The overall AUC value regardless of size of lesion was 0.791 for periapical radiography, and 1.000 for CBCT ($p=0.027$), refer to table 2.4.

The kappa value for overall inter-examiner agreement was 0.351 and 0.641 for periapical radiography and CBCT respectively. The mean intra-examiner agreement was 0.509 and 0.722 for periapical radiography and CBCT respectively (table 2.5).

	Sensitivity		Specificity		PPV		NPV	
Examiner	X ray	CBCT	X ray	CBCT	X ray	CBCT	X ray	CBCT
1	0.2	1	1	1	1	1	0.545	1
2	0.2	1	1	1	1	1	0.545	1
3	0.2	1	1	1	1	1	0.545	1
4	0.2	1	1	1	1	1	0.545	1
5	0.2	1	1	1	1	1	0.545	1
6	0.2	1	1	1	1	1	0.545	1
Mean (SD)	0.2 (0)	1	1 (0.0)	1	1 (0.0)	1	0.545 (0.0)	1
p value*	0.014		0.014		0.014		0.014	

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity.

Table 2.1. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing small periapical lesions using periapical radiographs (X ray) and CBCT.

	Sensitivity		Specificity		PPV		NPV	
Examiner	X ray	CBCT	X ray	CBCT	X ray	CBCT	X ray	CBCT
1	0.2	1	1	1	1	1	0.545	1
2	0.5	1	1	1	1	1	0.600	1
3	0.2	1	1	1	1	1	0.545	1
4	0.5	1	1	1	1	1	0.600	1
5	0.2	1	1	1	1	1	0.545	1
6	0.5	1	1	1	1	1	0.600	1
Mean (SD)	0.35 (0.16)	1	1 (0.0)	1	1 (0.0)	1	0.573 (0.03)	1
p value*	0.024		0.024		0.024		0.024	

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity.

Table 2.2. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing large periapical lesions using periapical radiographs (X ray) and CBCT.

	Sensitivity		Specificity		PPV		NPV	
Examiner	Xray	CBCT	Xray	CBCT	Xray	CBCT	Xray	CBCT
1	0.2	1	1	1	1	1	0.375	1
2	0.333	1	1	1	1	1	0.400	1
3	0.2	1	1	1	1	1	0.375	1
4	0.333	1	1	1	1	1	0.400	1
5	0.091	1	1	1	1	1	0.353	1
6	0.333	1	1	1	1	1	0.400	1
Mean (SD)	0.248 (0.10)	1	1 (0.0)	1	1 (0.0)	1	0.384 (0.02)	1
p value*	0.026		0.026		0.026		0.026	

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity: p=0.026

Table 2.3. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing all (small & large) periapical lesions using periapical radiographs (X ray) and CBCT.

	Small lesions		Large lesions		Small & large lesions	
Examiner	X ray	Cone beam	X ray	Cone beam	X ray	Cone beam
1	0.833	1.000	0.917	1.000	0.875	1.000
2	0.917	1.000	0.917	1.000	0.917	1.000
3	0.667	1.000	0.750	1.000	0.708	1.000
4	0.722	1.000	0.806	1.000	0.764	1.000
5	0.750	1.000	0.667	1.000	0.708	1.000
6	0.764	1.000	0.778	1.000	0.771	1.000
Mean (SD)	0.766 (0.088)	1.000 (0.000)	0.860 (0.098)	1.000 (0.000)	0.791 (0.087)	1.000 (0.000)
p value*	0.028*		0.027*		0.027*	

* p value from Wilcoxon matched=pairs, signed-ranks test

Table 2.4. AUC values from ROC analysis of periapical radiographs (X ray) and CBCT for individual examiners: Comparison of no lesions with small only, large only, and both small and large lesions.

Examiner	X ray	Cone beam
1	0.386	0.670
2	0.294	1.000
3	0.182	0.686
4	0.667	0.531
5	1.000	ND
6	0.526	ND
Mean (SD)	0.382 (0.295)	0.722 (0.198)
Inter-examiner kappa	0.351	0.641

ND = not done

Table 2.5. Kappa values for intra- and inter-examiner agreement in reading periapical radiographs (X ray) and CBCT images. The mean was based on 4 examiners only.

2.4 Discussion

Periapical lesions were created immediately below the distal root of first molar tooth as it was surrounded by more cancellous bone than its mesial counterpart, this also perhaps explains why periapical radiolucent lesions are usually first detected on the mesial root(s) of mandibular first molars (Bender 1982). The distal root was also easier to extract without damaging it as it tended to be straighter than the mesial root. The periapical lesions were 'machined' into the cancellous bone using a laboratory bur to allow standardised lesions of 2 different dimensions to be assessed (van der Stelt 1985, Barbat *et al.* 1998, Stavropoulos & Wenzel 2007). Other studies have used acid to create lesions which are claimed to have a more life like appearance (Tirrell *et al.* 1996, Ozen *et al.* 2008). However, the disadvantage of this method is that the size of the lesions may vary depending on the density of bone being prepared thus leading to heterogeneity of lesion size. It has been suggested that the detection of artificially created lesions should be easier than those occurring naturally, because of the marked variation in density at the outer border of the cavity, relative to the normal trabecular pattern (Lee & Messer 1986), however, this was the only way of standardising periapical lesions.

A diagnostic test is used to classify individuals as having a particular disease or not. The only accurate way to assess the ability of a diagnostic test is to compare the results with the true situation i.e. there must be a known 'reference' or 'gold standard' (Wilson 2007, Shiraishi *et al.* 2009). In this study the investigator knew the periapical status of the each mandible as he confirmed the absence of a periapical lesion prior to machining periapical lesions of predetermined sizes.

The use of ROC is an appropriate statistical approach for analysing radiological data, and accounts for bias in sample populations and the observers' tendency to over read and under read an image (Gelfnad & Ott 1985). ROC is constructed by finding the sensitivity and specificity for a range of values of x, and plotting sensitivity on the vertical axis, and 1 minus specificity (proportion of false positives) on the horizontal axis. ROC analysis is the most comprehensive description of diagnostic accuracy (Metz 2006), and is independent of the prevalence of the disease being assessed. It includes all cut-off points (in this study there were 5 cut-off points), rather than the binary cut-off (present/absent) generated when calculating sensitivity or specificity values (Obuchowski 2003). Sensitivity is defined as the proportion of those with disease who are correctly identified as having the disease (i.e. true positives), whereas specificity as the proportion of those without disease who are correctly identified as not having the disease (i.e. true negatives). Ideally, a diagnostic test has to be both sensitive and specific. However, as one is increased, the other is frequently reduced.

ROC also allows the overall diagnostic accuracy to be expressed as a single figure (AUC value), which is particularly helpful when comparing different systems. This has resulted in ROC analysis being used extensively in dental and medical assessment of radiological systems (Gatsonis 2009). The closer the AUC value is to 1 the more diagnostically accurate the system (the same applies to sensitivity and specificity values). Another technique to assess diagnostic

accuracy is by using positive predictive value or negative predictive value of a test. The PPV of a test are defined as the proportion of patients with a positive test results correctly diagnosed as such (Altman & Bland 1994). It differs subtly to sensitivity, in that it is dependent on the prevalence of the disease.

The ROC curve enables the best cut-off point for the diagnostic test to be determined. The point on the curve closest to the top left hand corner represents the best cut-off point for the division between disease and health, and when comparing more than one diagnostic test, those with curves closest to the top left hand corner are usually better tests.

As well as being able to detect the presence or absence of disease, a good diagnostic test must be repeatable. This repeatability should be tested both within and between examiners to ensure that the test will provide similar results when used by the same operator under similar conditions on different occasions, and similar results when used by different operators under similar conditions (Wilson 2007). Most radiological diagnostic methods use the kappa test for this situation. The kappa test is based on a contingency table of the repeated measures on individuals, either between occasions for one examiner or between examiners.

A test that is perfectly reproducible would provide a series of parallel diagnoses between 2 viewing sessions. Usually, a number of diagnoses on the second occasion do not match those on the first. The kappa statistic is calculated and provides a measure of the degree of the agreement between the two occasions that is greater than expected by chance. Kappa values range from 0 for no better than chance to 1 for perfect agreement. Opinions differ on the level that should be achieved, depending on the test and the disease being diagnosed. In general, scores between 0.61-0.80 may be interpreted as a 'substantial' strength of agreement, and scores between 0.81-1.00 an almost perfect agreement.

Whereas scores of <0.20, 0.21-0.40 and 0.41-0.60 may be interpreted as only a slight, fair and moderate strength of agreement, respectively (Landis & Koch 1977).

The present investigation compared the efficacy of periapical radiography and reconstructed CBCT images in detecting artificial periapical lesions limited to the cancellous bone in human mandibles. The results of this study suggest that CBCT imaging of teeth with endodontic problems (for example, pulpitis and periapical periodontitis) is of value. This investigation showed that periapical radiography was not sensitive at detecting periapical lesions of either size; the overall sensitivity was 0.248 (24.8%). However, the periapical radiography was more accurate at diagnosing 'large' periapical lesions than 'small' periapical lesions. This probably reflects the increased volume of bone destruction, and is in agreement with the findings of Paurazas *et al.* (2000). This may also explain why Sogur *et al.* (2009) found that periapical lesions created by longer applications of acid resulted in an increased accuracy of periapical radiographs.

Periapical radiography was accurate in confirming when periapical lesions were not present, in this situation there was 100% accuracy (specificity 1.0). CBCT was 100% accurate in diagnosing the presence (sensitivity 1.0) and absence (specificity 1.0) of periapical lesions. ROC analysis confirmed that CBCT was significantly more accurate than periapical radiography in detecting the presence of periapical disease. The overall diagnostic accuracy of periapical radiographs (ROC AUC value 0.791) in this study was in the same order of magnitude as other studies assessing artificial periapical lesions within the cancellous bone using digital (CCD) periapical radiography (Kullendorff *et al.* 1996, Paurazas *et al.* 2000). It is also likely that similar results would have been achieved with conventional periapical radiographic films (Kullendorf *et al.* 1996, Özen *et al.* 2008, Soğur *et al.* 2012).

The results of the sensitivity, specificity, PPV, NPV and ROC analysis of periapical radiographs in the present investigation are also similar to the findings of a recent clinical study (Estrela *et al.* 2008). In the clinical setting, the detection of periapical lesions may have been even poorer with periapical radiography due to the additional problem of less than ideal irradiation geometry associated with the difficulty in placing image receptors in an ideal position in certain regions of the oral cavity. In addition divergent roots may also be displayed with varying degrees of distortion on radiographs (Loftag-Hansen *et al.* 2007).

In clinical practice a variety of additional factors may affect the detection of periapical radiolucencies with CBCT, including observer performance, beam hardening and patient related factors. Observer performance was enhanced in the present study by ensuring that the periapical lesions had clear borders, which were probably easier to detect than natural periapical lesions. Beam hardening and image degradation from root fillings and restorations was eliminated by ensuring that all the teeth in the samples were unrestored and had no existing root(end) canal fillings. It is possible that in the clinical situation the quality of the reconstructed CBCT images produced may be less than ideal, for example, beam hardening and patient movement may reduce the diagnostic yield of the reconstructed images produced (Scarfe & Farman 2008).

It would have been desirable to use human cadavers to accurately reproduce soft tissue attenuation and scatter from the CBCT X ray beam. However, as this study was being carried out in an unlicensed area (private practice) rather than a University Institution this was not possible due to Government legislation (Human Tissue Act 2004). Therefore dry mandibles rehydrated in soapy water were used. Prosthetic dental wax was used as a soft tissue substitute as it has the same optical density as human soft tissue (Ricketts *et al.* 1995, 1997). Pilot studies

confirmed that the radiographic and CBCT appearance of this mandible model closely replicated clinical images on patients.

The results of this study appear to validate clinical studies that have used CBCT as the 'gold standard' for determining the presence or absence of periapical lesions (Lofthag-Hansen *et al.* 2007, Estrela *et al.* 2008, Low *et al.* 2008, Bornstein *et al.* 2011). CBCT has evolved from Computed tomography (CT). Essentially the collected raw data from both imaging techniques may be formatted and viewed in similar ways. Velvart *et al.* (2001) found that CT was 100% accurate in detecting the presence of periapical lesions compared with 78% for periapical radiographs. The higher detection rate of periapical lesions with periapical radiographs in this study may have been due to long-standing chronic periapical periodontitis, which may have eroded the cortical bone. It would have been interesting to correlate the adjacent cortical bone involvement as seen on coronal CT slices to the corresponding radiographs. Similar results were also found by Huuonen *et al.* (2006) when they assessed maxillary molar teeth. The reduced accuracy of periapical radiography in detecting periapical lesions compared with CT or CBCT technology in these clinical studies and the present study was due to the lesions being confined to the cancellous bone only, and being masked by the denser, more mineralised cortical plate. Subtle changes in bone density, trabeculae architecture, bone marrow spaces and morphological variations in the apical region may also be missed (Halse *et al.* (2002).

Our findings are in agreement with other *ex-vivo* investigations which have used a reference standard, these studies also found that CBCT is more accurate than periapical radiographs at detecting the presence or absence of periapical radiolucencies (Stavropolous & Wenzel 2007, Özen *et al.* 2008, Paula-Silva *et al.* 2009a), this will be discussed in more detail in the chapters 4 and 5.

With CBCT the examiner usually specifies the orientation of the reconstructed slice(s) resulting in orthogonal views that are parallel and perpendicular to the long axis of the root under investigation. In addition the thickness of each slice (i.e. how much information) and the interval between each slice can be adjusted. These factors ultimately result in periapical lesions being significantly more perceptible to the examiner compared with periapical radiographs as the CBCT software may be used to maximise the diagnostic yield of the captured data in each case. In addition, the reconstructed slices are geometrically accurate. Therefore, periapical lesions will not change size or disappear on reconstructed scans as can happen with periapical radiography as a result of poor irradiation geometry (Gröndahl & Huuonen 2004). Not only can the presence of a periapical lesion(s) be diagnosed with CBCT, but the specific root that it is associated with can also be confirmed. This may influence treatment planning (Lofthag-Hansen *et al.* 2007).

A digital periapical radiographic system rather than a conventional X-ray film was used in this study as the resulting image was dynamic and therefore could be easily enhanced (contrast/brightness) to improve the diagnostic yield of the radiographic image (Kullendorff & Nilsson 1996). Several studies have shown that there is no difference in the detectability of artificially created periapical lesions using conventional X ray films and digital sensors (Kullendorff and Nilsson 1996, Barbat & Messer 1998, Stavropolous & Wenzel 2007, Özen *et al.* 2009), or between different direct digital sensors (Folk *et al.* 2005). Enhancing the radiographic images (for example, 'colourizing' and inverting) with software was not carried out as it has not been shown to enhance the detection of periapical lesions (Barbat & Messer 1998). It could be argued that the detection rate of periapical lesions with radiographs may have been higher if parallax radiographs were taken of each tooth (Brynnolf 1970a, b), and if a consensus agreement between all the examiners was reached for each case (Molven *et al.* 2002).

The periapical radiographs were viewed as PowerPoint slides. Theoretically transferring digital images to PowerPoint may affect the quality (for example, spatial resolution) of the radiographs, but, with care, this is unlikely (Durack *et al.* 2011). Steps were taken during the original process of saving the images to minimize any reduction in image quality associated with the preparation of the slides. Before the examiners were shown the experimental data, the original images were closely inspected and compared with the same images on PowerPoint slides. No subjective difference in image quality was noticed by the author.

There is a school of thought that believes that periapical lesions confined to the cancellous bone and not affecting the cortical plate cannot be detected using periapical radiography (Bender & Seltzer 1961, Radaman & Mitchell 1962, Schwartz & Foster 1971, Bender 1982). However, in the present study a number of periapical lesions confined to cancellous bone were detected using periapical radiography. Similar findings have been reported by other investigators (Barbat & Messer 1988, Marmary *et al.* 1999, Paurazas *et al.* 2000, Wallace *et al.* 2001).

The inter-examiner and intra-examiner agreement between the examiners was higher with reconstructed CBCT images, suggesting that CBCT scans are perhaps easier to interpret compared with periapical radiographs. Goldman *et al.* (1972, 1974) found inter-examiner agreement between their 6 examiners was 47% and intra-examiner agreement was between 74% and 80% using periapical radiographs. Reit & Hollender (1983) found only 39% agreement between examiners, they suggested that the greatest diagnostic difficulty encountered was when the more subtle signs of periapical inflammatory changes were assessed (i.e. widened periodontal ligament space or small periapical lesions). Reit (1987) suggested that observer calibration may be of limited value in reducing the

incidence of observer disagreement, and suggested that this may be partly due to the scientific, psychological and sociological aspects of decision-making process.

Similar results were presented by Zakariasen *et al.* (1984), who reported that inter-examiner agreement was only 38%, and intra-observer agreement was between 64.5 and 81%. Although not directly comparable with the Kappa results in this study, they do seem to suggest a similar level of agreement. Özen *et al.* (2008) also found CBCT to be more reliable (higher inter-examiner and intra-examiner agreement) than periapical radiographs for detecting periapical radiolucencies.

Evidence-based selection criteria for the use of CBCT are required (Patel *et al.* 2007, Patel 2009). Radiation exposure to patients should be kept as low as reasonably practicable (ALARP). As described in chapter 1, the effective radiation dose from CBCT is higher than conventional radiography, therefore when considering taking a CBCT scan the benefits of this investigation must outweigh any potential risks to the patient (Patel & Horner 2009). The radiation dose also varies significantly depending on the scanner used, the region being scanned and the exposure parameters selected (Loubule *et al.* 2009, Roberts *et al.* 2009, Lennon *et al.* 2011). Interestingly, the excellent results with CBCT in the present investigation were achieved despite the fact that the Veraviewpocs® CBCT scanner used only had a 180° arc, therefore resulting in a significantly lower radiation dose.

The results of this study provide evidence of CBCT's validity and reliability for detecting the presence of periapical lesions. Further investigations are required to determine the diagnostic validity of different CBCT scanners, and the effect of changing the exposure parameters on the detection of periapical lesions.

Periapical radiography, which is the imaging technique of choice for the management for periapical disease, appears to be quite crude on both accounts (validity and reliability) in the detection of periapical lesions. The superior accuracy of CBCT may result in a review of the radiographic techniques used to assess the presence of periapical lesions in outcome and epidemiological studies since the prevalence of periapical disease may be significantly under-estimated with conventional radiography (Estrela *et al.* 2008, Patel *et al.* 2011, Wu *et al.* 2011).

2.5 Conclusion

This study indicates that CBCT results in improved detection of the presence and absence of simulated periapical lesions.

External factors (i.e. anatomical noise, poor irradiation geometry), which are not in the operators control with periapical radiography, dictate what might or might not be revealed on a conventional periapical image. CBCT limits the effect of such external factors.

Chapter 3

3. The detection of vertical root fractures in root filled teeth using periapical radiographs and CBCT scans.

3.1 Introduction

Vertical root fracture (VRF) often affects endodontically treated teeth (Llena-Puy *et al.* 2001), often resulting in tooth loss (Torbjörner *et al.* 1995, Caplan *et al.* 1997, Sathorn *et al.* 2005). The prevalence of VRF in endodontically treated teeth has been reported to be between 3% and 13% (Testori *et al.* 1993, Torbjörner *et al.* 1995, Fuss *et al.* 1999, Touré *et al.* 2011). A recent study looking at the reasons for extraction of endodontically treated teeth concluded that 32% of extracted teeth were fractured (Chen *et al.* 2008). The prevalence of vertical root fracture is reported to be higher in endodontically treated teeth than in vital teeth (Cohen *et al.* 2003, Chan *et al.* 1999).

The aetiology of VRF includes: unfavourable root and root canal morphology (Sathorn *et al.* 2005), over-zealous instrumentation of the root canal system (Sathorn *et al.* 2005, Kim *et al.* 2010), obturation (Holcomb *et al.* 1987), inappropriate restoration after endodontic treatment (Fuss *et al.* 2001, Kishen *et al.* 2006) and excessive occlusal forces (Kamburoğlu *et al.* 2010).

Clinical features of VRF include: direct visualisation of a fracture line, one or more sinus(es), a deep narrow isolated periodontal probing depth on one or both sides of the VRF, and mobility (Meister *et al.* 1980, Pitts & Natkin 1983). Radiologically there may be a halo or 'J' shaped radiolucency around the fractured root or even complete separation of the fractured root (Tamse *et al.* 1999, Tamse 2006). A combination of these clinical and radiological signs and symptoms is pathognomic of VRF (Llena-Puy *et al.* 2001). However, in certain instances the diagnosis is not so straight forward. A recent systematic review assessing the

clinical features of VRF concluded that there was a lack of evidence-based data regarding the diagnostic accuracy of commonly used clinical and conventional radiographic signs for diagnosing VRF (Tsesis *et al.* 2010). This is particularly the case with incomplete fractures where there are no associated specific patterns of peri-radicular bone loss (Tamse *et al.* 1999, 2006).

Inappropriate management can arise from the inability to formulate a definitive diagnosis, or from misdiagnosing a VRF as a localised periodontal problem or a failed endodontic treatment (Mesiter *et al.* 1980, Tamse 2006). An accurate diagnosis is essential to prevent potentially unnecessary treatment as a result of misdiagnosis, and to allow the tooth in question to be extracted as soon as practically possible to reduce unnecessary alveolar bone loss (Özer 2010). This is particularly relevant when an implant retained crown restoration is planned as a future replacement of the extracted tooth.

Endodontic malpractice is a common cause of patient's claims of negligence (Bjørndal & Reit 2008). VRF following root canal treatment may result in a liability claim (Rosen *et al.* 2011). Therefore, from a medico-legal perspective, accurate and timely diagnosis is desirable.

Conventional film and digital based radiographic systems have several limitations for diagnosing VRF. These include the fact that the X-ray beam must pass through the fracture line for it to be detected (Tsesis *et al.* 2008). Furthermore, compression of the complex anatomy into a 2 dimensional 'shadowgraph', and the overlying anatomy (anatomical noise) masking the area of interest may also hinder diagnosis (Cotton *et al.* 2007, Patel *et al.* 2009, Wang *et al.* 2011).

Youssefzadeh *et al.* (1999) published one of the first studies to assess the viability of 3-dimensional imaging to diagnose VRF using CT. They compared a

periapical radiograph with CT to assess 42 teeth with suspected VRF and found that CT was far more accurate than periapical radiography at diagnosing VRF. Hanning *et al.* (2005) published a case series report assessing VRF in root treated teeth using CBCT. Other studies have followed which have shown that CBCT is more accurate than radiographs in determining the presence of VRF (Hassan *et al.* 2009a, Wang *et al.* 2011).

Wang *et al.* (2011) assessed 135 teeth *in-vivo* with clinical symptoms and/or signs of VRF; both untreated and root treated teeth were assessed, the radiographic findings (periapical radiographs and CBCT images) were confirmed by clinical inspection or extraction of the root/tooth under investigation. They found that CBCT was less sensitive when VRF was being detected in presence of gutta percha, however the specificity was not significantly influenced.

To date, only one study has measured the widths of the VRFs created (Özer 2010). In this study VRFs of specific widths, (0.2mm & 0.4mm were created; and it was found that CBCT was more accurate than digital radiographs at diagnosing 0.2mm and 0.4mm wide fractures. No studies have attempted to replicate the dimensions of *in vivo* VRFs into an *ex vivo* setting or model. This type of assessment would allow a more standardised *ex vivo* model for assessing VRFs.

The aim of this investigation was to compare *ex vivo*, the diagnostic accuracy of CBCT systems with periapical radiography in detecting artificially prepared incomplete and complete VRFs in human teeth.

3.2 Materials and Methods

3.2.1 Determination of root fracture width in teeth clinically diagnosed with vertical root fractures.

Five previously extracted mandibular root treated premolar and molar teeth diagnosed with VRF were cleaned using a toothbrush and water to remove gross debris. A dental operating microscope (3 step entrée Dental Microscope, Global) was used to confirm the presence of incomplete VRF. The maximum width of these VRFs was determined using a light microscope with video-based measuring system, (Galileo EZ300, Starrett, Athol, MA, USA), and confirmed using an optical coherence tomography scanner (VivoSight, Michelson Diagnostics, Orpington, UK). The maximum width of these cracks varied from 30 to 100µm.

3.2.2 Ex vivo investigation

Subject material

14 mandibular premolar and 14 mandibular molar teeth from 10 dry human mandibles were used for this investigation (Department of Anatomy and Human Sciences, King's College London, University of London). Each mandible was soaked for 90 minutes in warm water into which hand dish washing liquid was added as described in chapter 2.

The teeth were extracted a traumatically. The teeth were inspected with the aid of a light microscope (Galileo EZ300) to confirm the absence of VRFs. The teeth were then firmly replaced in their sockets. Baseline radiographs and CBCT scans were taken (see below).

Existing restorations were removed, and access cavities were prepared in each tooth. The canals were initially negotiated and patency was confirmed with a size 10 K Flexofile® (Dentsply-Maillefer, Baillagues, Switzerland).

The canals were then prepared to a size 20 master apical file using a crown-down technique with K Flexofile®, after which hand ProTaper® instruments (Dentsply Maillefer) were used according to the manufacturer's instructions to prepare the canals up to a F2 master apical rotary file. Patency was maintained and the canals were irrigated with 2% sodium hypochlorite (Chlorax 2%, CerkaMed, Sandomierska, Poland) between the introduction of each instrument. A suitable sized gutta point (ProTaper® Gutta Percha, Dentsply Maillefer) which gave tug back 1mm short of the working length was then inserted into the prepared root canal. A jig was made to allow accurate repositioning of the mandibles at each stage of the investigation. Periapical radiographs and CBCT scans were then taken (group 1, no VRF [control]).

The teeth were re-extracted atraumatically and embedded in vinyl polysiloxane impression putty (Express STD Firmer Set, 3M ESPE AG, Seefeld, Germany) in a steel cylinder (diameter 20mm, height 30mm), which was placed on a fixed platform of an Instron 5569A Universal Testing Machine (Instron, Norwood, MA, USA). The tip of a sewing needle (Milward short darning size 5, Coats, Kenzingen, Germany) was inserted into the prepared canal and its head was fixed in a metal chuck, which was in turn attached to the cross-head of an Instron machine (figure 3.1). The machine was programmed for the cross-head to force the needle apically into the canal at a rate of 1mm min⁻¹: the force applied was recorded using a dedicated software package (Bluehill 2, Instron). The machine was programmed to cease the load application if a sudden drop in force of greater than 20% was recorded. By controlling the force applied an incomplete fracture could be induced. The tooth was then removed from the putty matrix and inspected using a light microscope with video-based measuring system, (Galileo

EZ300) for the presence of incomplete VRFs. Optical coherence tomography scanner (VivoSight, Michelson) was used to determine the width of the cracks. An incomplete VRF was classified as being a (microscopically) visible crack within the root which could not be separated with a wedging force (Rivera & Walton 2009).

Any distal roots of molar teeth with cracks on the mesial aspect of the root were removed from the investigation as it was not possible to determine the width of these cracks.

The teeth were then re-implanted into the extraction sockets and a gutta-percha point was then re-inserted into the canal and another series of radiographs and CBCT scans were taken (group 2, incomplete VRF). To create complete fractures, a similar protocol was used as that to create incomplete fractures, but a larger sewing needle was used (Milward short darning size 3, Coats). The load was then re-applied using the Instron machine as previously described. The force delivered was monitored carefully to determine when a complete vertical root fracture may have occurred. The tooth was then removed from its putty matrix and inspected for the separation of the root fragments. The gutta percha point was then reinserted and radiographic images were taken again (group 3, complete VRF). A complete VRF was defined as a complete separation of the root fragments (Rivera & Walton 2009). The same tooth was used in group 1, 2 and 3.

In total 9 premolar teeth and 11 molar teeth were used for group 1 and 2, and 5 premolars and 2 molars were used in group 3. The remaining teeth were excluded as they either had existing cracks in the root, or fractured catastrophically as they were being extracted.

The OCT scans were taken along the entire length of the incomplete fractures (at 0.1mm intervals). The width of the fracture varied along the length of the root, therefore the maximum width of the fracture was noted. The position of the widest part of the crack was noted, so that when selecting the scans for the examiners, the most relevant part of the tooth could be displayed. The maximum width of incomplete fractures created varied from 50 to 110 μ m.

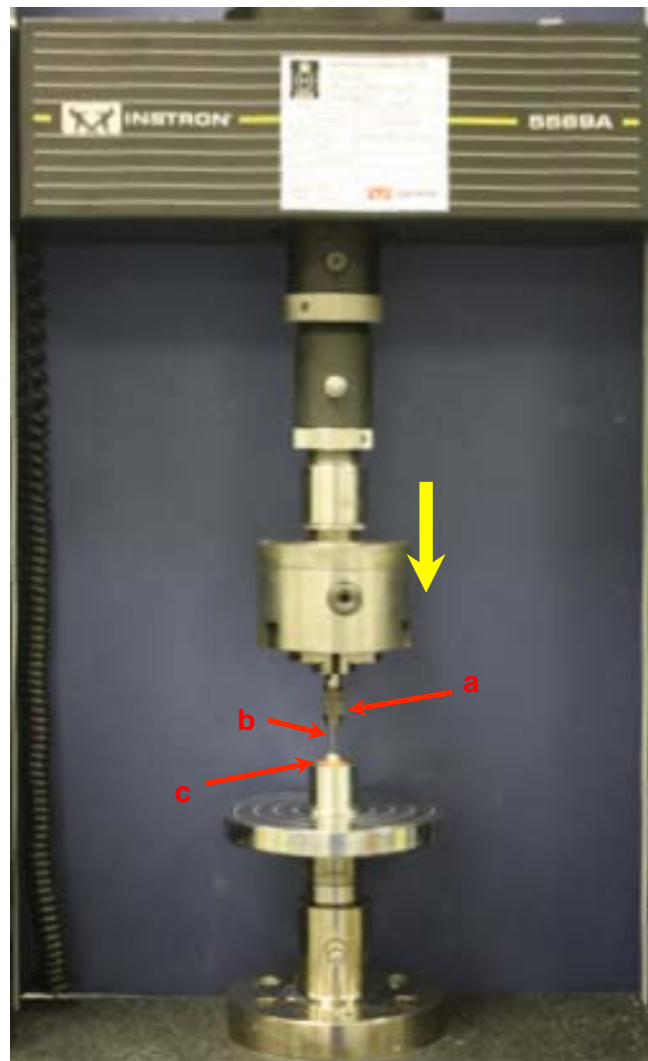


Figure 3.1. Instron machine used to create (in)complete fractures. (a) Chuck securing (b) sewing needle, which gradually enters the access cavity of the tooth housed in putty within a metal cylinder (c). The yellow arrow indicates the direction of the force.

3.2.3 Radiographic technique

Two specifically designed jigs were made for the radiographs and the CBCT scans to allow accurate repositioning of the mandibles at each stage of the investigation.

Periapical radiographs-The jig used for the periapical radiographs enabled each tooth to be positioned at a consistent distance (35cm) from the X-ray source. A separate jig was constructed for each mandible. The methodology for the construction and use of the jig is described in chapter 2.

A digital photostimulable phosphor plate (PSP) system (Digora® Optime, Soredex, Tuusula, Finland) was used to take periapical radiographs. The phosphor plates were held in place with a standard periapical radiograph film holder (Dentsply Rinn, Elgin IL, USA). Radiographs were exposed using a dental X-ray unit (Heliodent, Sirona, Bensheim, Germany) operating at 65kV, 7mA and 0.16 seconds.

CBCT-A separate jig was used for each mandible as with the periapical radiographs. The jig consisted of a series of polyvinyl-siloxane impression material putty indices (President). One (lower) surface of the impression material was moulded onto a plastic canister, the lower border of each mandible was gently pushed 3-4mm into the upper surface of the impression material and left in place until the impression material set. This allowed each mandible to be seated in the same reproducible position on the plastic canister. The mandible and plastic canister were then placed on a wooden box and seated in the Accuitomo 3D CBCT scanner (J. Morita) ready for imaging. Each jig and mandible was labelled. Reference points were made to allow correct repositioning of the jig in

the CBCT scanner. Each mandible was positioned with the long axis the tooth under investigation approximately perpendicular to their supporting platform. This reduced the amount of up-righting of the data which would be required using the CBCT software.



Figure 3.2. Jig used to position mandible in CBCT scanner. (a) CBCT X ray source, (b) reciprocal detector, (c) mandible mounted within impression material to ensure accurate repositioning, (d) plastic cylinder, (e) acrylic hollow cylinder.

A hollow cylinder of acrylic, (Plexiglas®, Evonik Industries AG, Essen, Germany) (300mm diameter, 500mm height and 5mm thickness) was placed around the mandible to attenuate the beam, thus mimicking the soft tissues in the clinical situation (Figure 3.2). Exposure parameters of 90 kV, 3.0 mA and a 17.5 s scan were used for the CBCT scanner. All CBCT data were re-sliced to produce 0.16mm slice intervals and 1.2mm slice thickness. The brightness and contrast of all images were optimized to allow the best possible visualization of the VRFs.

3.2.4 Radiographic assessment

Six examiners (endodontists n=3, postgraduate endodontists n=3) individually assessed the periapical radiographs and CBCT scans in 3 sessions as follows: In session (1) Approximately half of the periapical radiographs (n=24) were assessed followed by half of the CBCT scans (n=23). In session (2) the consensus panel assessed the remaining CBCT scans (n=24) followed by the remaining periapical radiographs (n=23). Intra-examiner agreement of periapical radiographs (n=22) and CBCT scans (n=22) was assessed in session 3. Examples of the images assessed can be seen in Figures 3.3-3.5. There was at least a one week interval between each session, all images were viewed in a computer generated randomised sequence in each session. All the examiners were trained using examples of periapical radiographs and CBCT images with and without the presence of VRF before embarking on the assessment. These radiographic images did not belong to the experimental sample.

The images were viewed as a PowerPoint® (Microsoft) on a laptop computer (MacBook Pro®, Apple, CA, USA) which had a screen pixel resolution of 1690 X 1050. A VRF was defined as a vertical or oblique radiolucent line running along the surface of the root.

A CBCT image that best confirmed the presence or absence of a VRF in the sagittal and coronal planes was chosen by the author as the starting point for each tooth observation. Examiners also had access to the raw CBCT data allowing them to scroll through any of the orthogonal scans. All images were assessed in a quiet dimly lit room. The examiners were trained and calibrated before embarking on the assessment.

Examiners were asked to note down the presence or absence of a VRF using a 5 point confidence scale as follows: 1 - VRF definitely not present, 2 - VRF

probably not present, 3 - unsure, 4 - VRF probably present, 5 - VRF definitely present. The examiners were not asked to differentiate between incomplete and complete fractures.

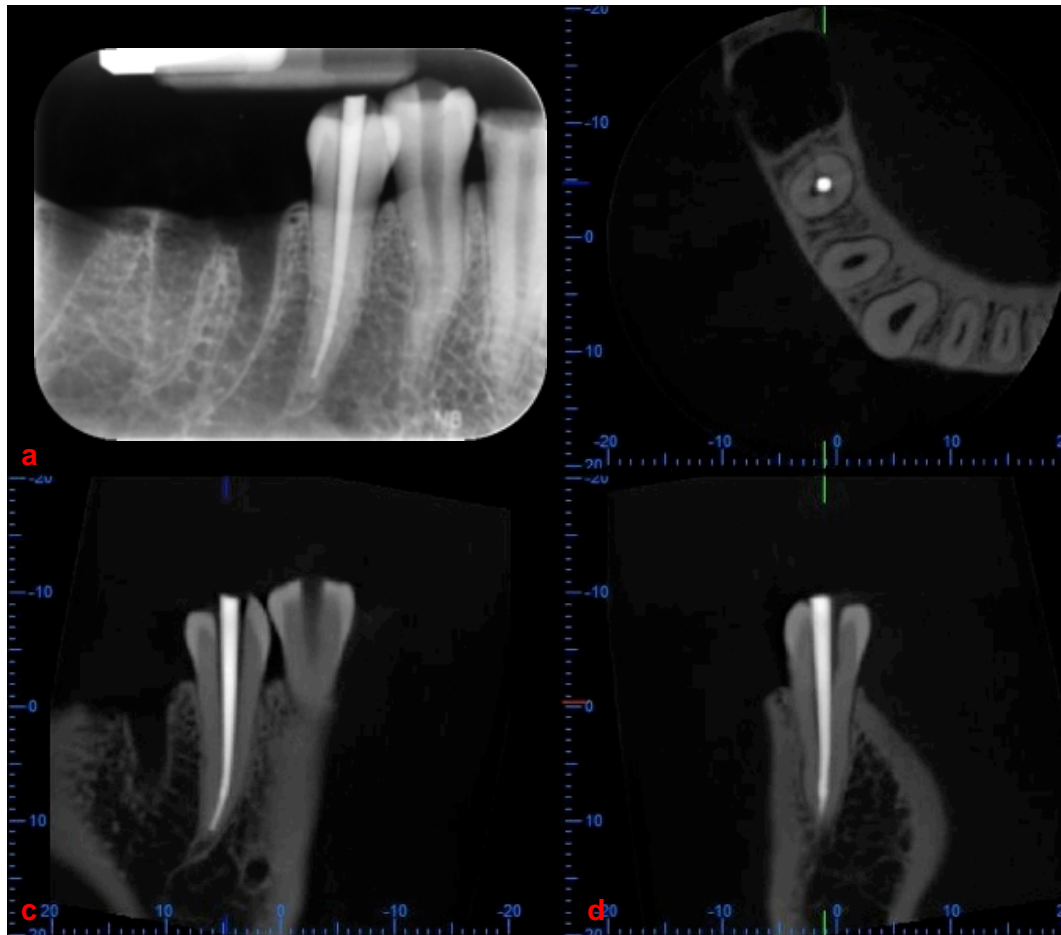


Figure 3.3. (a) Periapical radiograph, and (b) axial, (c) sagittal, and (d) coronal reconstructed CBCT images of a mandibular premolar tooth with no VRF.

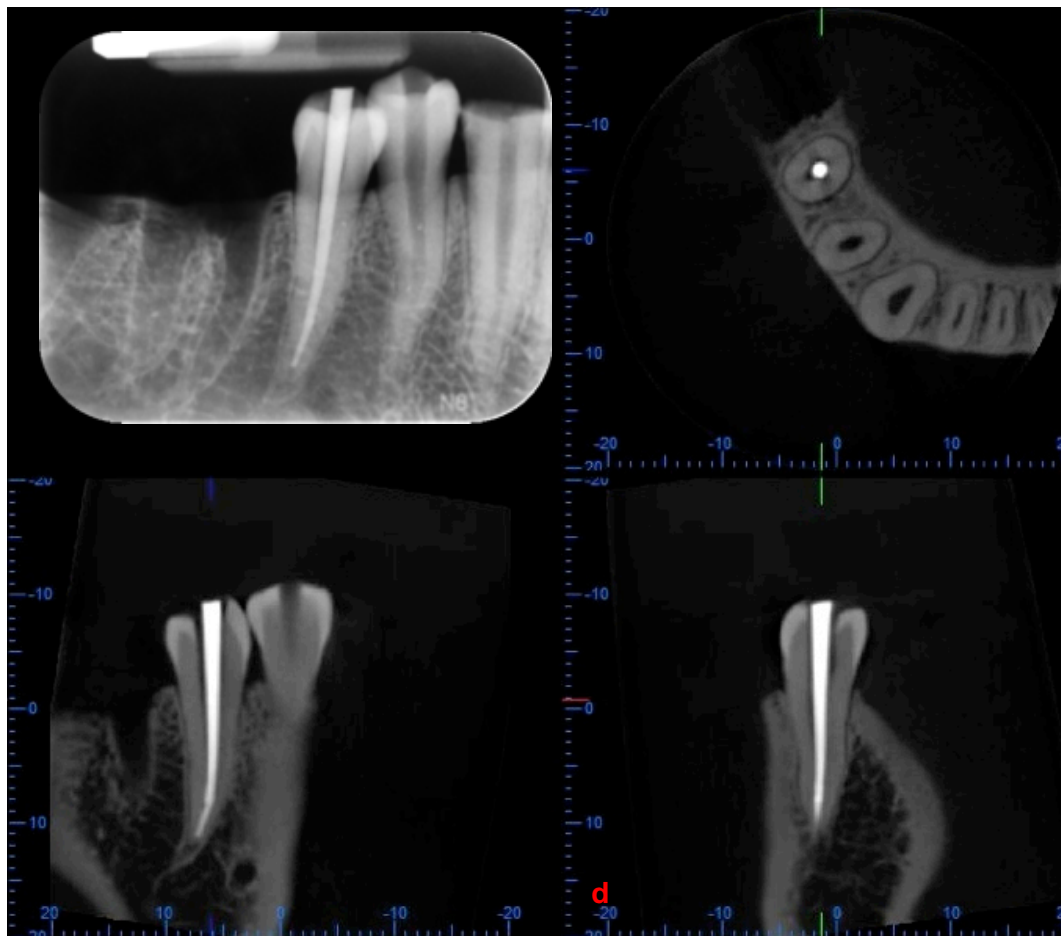


Figure 3.4. (a) Periapical radiograph, and (b) axial, (c) sagittal, and (d) coronal reconstructed CBCT images of the mandibular premolar tooth in figure 3.2 with an incomplete VRF.

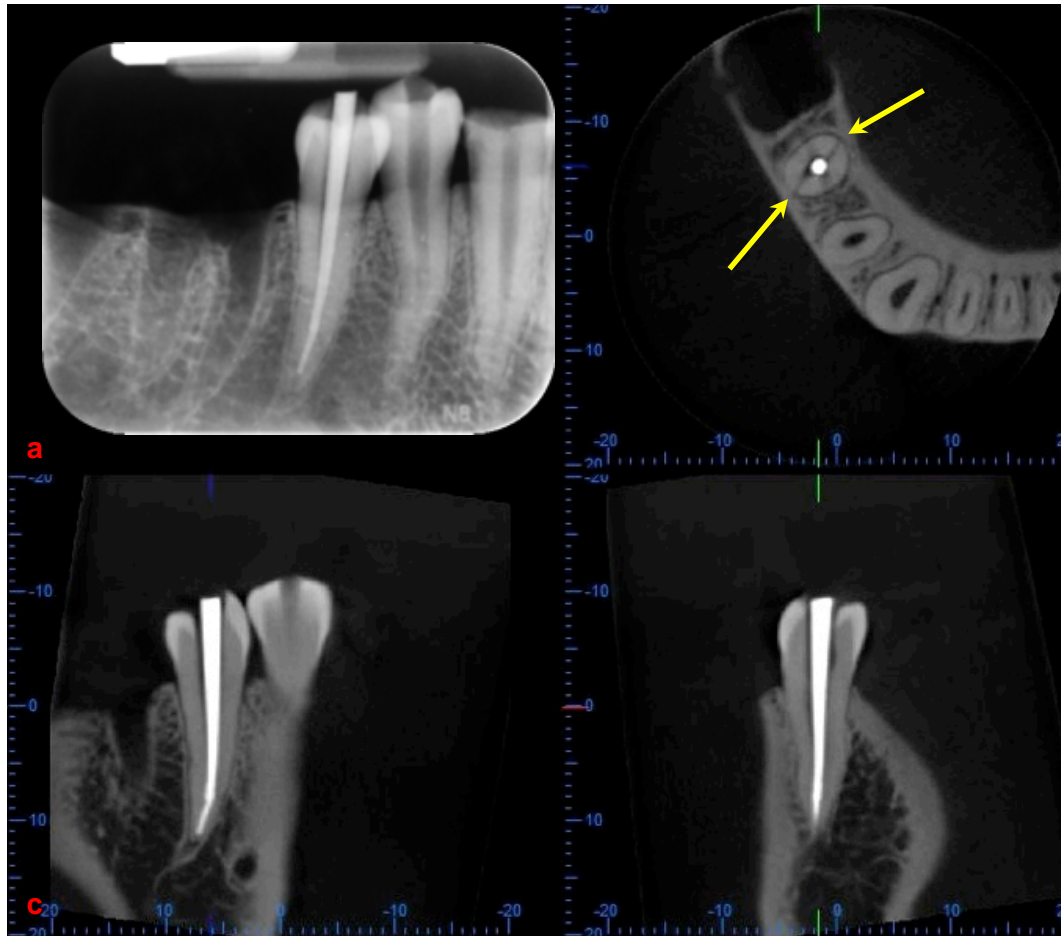


Figure 3.5. (a) Periapical radiograph, and (b) axial, (c) sagittal, and (d) coronal reconstructed CBCT images of the same mandibular premolar tooth in figure 3.2 & 3.3 with a complete VRF, note the VRF (yellow arrows) is more clearly delineated than the scatter.

3.2.5 Data analysis

Stata™ software (Stata 11) was used to analyse the data. Sensitivity, specificity and predictive values were determined; Diagnostic accuracy of each examiner and each imaging system for detecting the presence or absence of a VRF was determined using ROC curve analysis. Cut off points were 1-3 for no VRF, and 4-5 for incomplete/complete VRF. Inter-examiner and intra-examiner agreement was assessed by Kappa statistics.

Comparison of periapical radiographs and CBCT scans was achieved using Wilcoxon matched-pairs, signed ranks test of the six examiners' results. Statistical significance was inferred at $p < 0.05$.

3.3 Results

The sensitivity of CBCT for detecting the presence of both incomplete VRFs (0.53; $p=0.028$) and complete VRFs (0.69; $p=0.027$) was higher than periapical radiographs, which showed a sensitivity of 0 ($P=0.028$) and 0.19 ($P=0.027$) for incomplete and complete VRF, respectively. Periapical radiographs has a higher specificity than CBCT for detecting both incomplete and complete VRFs (table 3.1-3.2).

The overall sensitivity of periapical radiography (0.05) was lower than CBCT (0.57) regardless of the extent of the VRF ($p=0.027$), i.e. these techniques correctly identified VRFs in 5% and 57% of cases, respectively (table 3.3). Periapical radiographs had a higher overall specificity (0.98) than CBCT (0.34), ($p=0.027$).

Examiner	Sensitivity		Specificity		PPV		NPV	
	Xray	CBCT	Xray	CBCT	Xray	CBCT	Xray	CBCT
1	0	70	100	40	0	54	100	57
2	0	50	95	40	0	45	49	44
3	0	55	100	35	0	46	100	44
4	0	60	95	10	0	40	49	20
5	0	40	95	45	0	42	49	43
6	0	45	95	50	0	47	49	48
Mean (SD)	0 (0)	53.3 (10.8)	96.7 (2.6)	36.7 (14.0)	0 (0)	45.7 (4.8)	66.0 (26.3)	42.7 (12.3)
p value*	0.028		0.028		0.028		0.028	

*Wilcoxon matched-pairs, signed ranks test

Table 3.1. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing incomplete fractures using periapical radiographs (Xray) and CBCT.

Examiner	Sensitivity		Specificity		PPV		NPV	
	Xray	CBCT	Xray	CBCT	Xray	CBCT	Xray	CBCT
1	29	71	100	40	100	29	80	80
2	29	86	100	40	67	33	79	89
3	29	86	100	35	100	32	80	88
4	14	57	95	10	50	18	76	40
5	14	42	95	45	50	21	80	69
6	0	71	95	50	0	33	73	83
Mean (SD)	19.2 (11.9)	68.8 (17.1)	97.5 (2.7)	36.7 (14.0)	61.2 (37.5)	27.7 (6.6)	78.0 (2.9)	74.8 (18.5)
p value*	0.027		0.027		0.116		0.832	

*Wilcoxon matched-pairs, signed ranks test

Table 3.2. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing complete fractures using periapical radiographs (Xray) and CBCT.

Examiner	Sensitivity		Specificity		PPV		NPV	
	Xray	CBCT	Xray	CBCT	Xray	CBCT	Xray	CBCT
1	7	70	100	33	100	61	44	50
2	7	59	100	33	67	57	43	42
3	7	63	100	35	100	57	44	41
4	4	59	95	10	50	47	42	15
5	4	41	95	45	50	50	42	36
6	0	52	95	50	0	58	41	43
Mean (SD)	4.8 (2.8)	57.3 (9.9)	97.5 (2.7)	34.3 (13.8)	61.2 (37.5)	55.0 (5.3)	42.7 (1.2)	37.8 (12.1)
p value*	0.027		0.027		0.399		0.400	

*Wilcoxon matched-pairs, signed ranks test

Table 3.3. Sensitivity, specificity, positive predictive value (PPV) and negative predictive values (NPV) (%) for individual examiners diagnosing all fractures using periapical radiographs (Xray) and CBCT.

The overall AUC value of incomplete and complete VRF was 0.53 for periapical radiography, and 0.45 for CBCT ($p=0.034$), respectively. The ROC analysis for periapical radiographs revealed a higher AUC value (0.5) than CBCT (0.4) for the detection of incomplete VRFs ($p=0.043$). Similarly, the periapical radiograph's AUC value (0.57) for the detection of complete VRFs was also higher than that for CBCT (0.52), however, these results were not statistically significant ($p=0.5$) (table 3.4). The ROC curves can be found in Appendix II.

Examiner	Incomplete fracture		Complete fracture		All fractures	
	X ray	CBCT	X ray	CBCT	X ray	CBCT
1	0.500	0.504	0.699	0.553	0.552	0.519
2	0.500	0.400	0.617	0.515	0.547	0.430
3	0.500	0.426	0.737	0.647	0.576	0.479
4	0.500	0.316	0.549	0.440	0.516	0.350
5	0.501	0.413	0.620	0.466	0.535	0.426
6	0.503	0.474	0.323	0.534	0.460	0.489
Mean (SD)	0.501 (0.001)	0.406 (0.057)	0.569 (0.153)	0.520 (0.080)	0.531 (0.016)	0.449 (0.025)
p value*	0.043		0.500		0.034	

*Wilcoxon matched-pairs, signed ranks test

Table 3.4. AUC values from ROC analysis for diagnosis of incomplete and complete fractures for periapical radiographs (X ray) and CBCT.

The kappa value for overall inter-examiner agreement was 0.024 and 0.005 for periapical radiographs and CBCT, respectively. The mean intra-examiner agreement was 0.209 and 0.409 for periapical radiography and CBCT respectively (Table 3.5).

Examiner	X ray	CBCT
1	0.000	0.274
2	0.313	0.439
3	0.349	0.548
4	0.171	0.442
5	0.279	0.348
6	0.144	0.405
Mean (SD)	0.209 (0.130)	0.409 (0.093)
p value*	0.028	
Inter-examiner kappa	0.024	0.005

*Wilcoxon matched-pairs, signed ranks test

Table 3.5. Kappa values for intra- and inter-examiner agreement in diagnosing fractures using periapical radiographs (X ray) and CBCT.

3.4 Discussion

Simulated VRFs were created in teeth from dry mandibles. This had the advantage of standardising the order of magnitude of the fracture widths and root filling density. The soft tissue attenuation and scatter were simulated by encompassing the specimen within a hollow acrylic cylinder, the technique used in the present investigation has been successfully used by Lennon *et al.* (2011). A pilot study confirmed that the images captured using this soft tissue equivalent closely mimicked corresponding clinical images on patients. The pilot study images were assessed by an experienced Consultant Dental and Maxillofacial Radiologist who was not involved in the assessment of the experimental images. The use of human cadavers would have been preferable, however, for the reasons stated in chapter 2 this was not possible. A decision was made to use mandibles only, as intact series of suitable maxillas were not readily available. There is also evidence to indicate that root treated mandibular posterior teeth are usually the most commonly diagnosed with VRF (Tamse *et al.* 1999, Chan *et al.* 2006).

A digital phosphor plate intraoral periapical radiographic system rather than a conventional X-ray film was used in this investigation; like with charge couple radiographic system used in chapters 2 and 3-5 the resulting image was dynamic and therefore could be easily enhanced. Several studies have shown that there is no or minimal difference in the detectability of artificially created VRFs using conventional X-ray films and digital sensors (Kositbowornchai *et al.* 2001, Tsesis *et al.* 2008, Tofangchiha *et al.* 2011). Enhancing the radiographic images (for example, zooming in, colourizing and inverting) with software was not carried out as it has not been shown to enhance the detection of VRFs (Kositbowornchai *et al.* 2001). Parallax radiographs were not used in the present investigation, there is no evidence to suggest that 2 or more additional views aids diagnosis of VRF

(Tsesis *et al.* 2012). A GP point was inserted into the root canal to assess the influence of a radiodense material on the diagnostic quality of the images produced with CBCT.

Observers using periapical radiographs were not able to correctly identify any incomplete VRFs, and only 19% of complete VRFs. The marginally improved results with complete VRFs was most probably due the resolution of the radiograph allowing the wider break to be readily identifiable. Youseffzadeh *et al.* (1999) found the overall sensitivity and specificity of periapical radiographs to be 25% and 100%, respectively. In another study only 36% of VRFs could be detected on periapical radiographs (Rud & Omnell 1970). However, in their clinical study the reference standard was the surgical exposure of the tooth under investigation. In the present investigation incomplete and complete VRFs were detected with CBCT in 53% and 69% of cases, respectively.

In the present investigation periapical radiographs had nearly perfect accuracy in confirming when VRFs were absent. However, the specificity of CBCT was much poorer for assessing the absence of incomplete (0.37), and complete (0.37) fractures; these results were statistically significant. The AUC values confirmed that both periapical radiographs and reconstructed CBCT images were inaccurate for diagnosing VRF. The poor sensitivity of periapical radiographs in diagnosing VRFs was most probably due to several factors which included; poor resolution of the image, the compression of the anatomy and anatomical noise of the surrounding bone. One possible explanation for the high specificity was the fact that the majority of teeth were scored negatively regardless of a fracture being present or not (Hassan *et al.* 2009). The superimposition of one root over another in molar teeth as well as the X-ray beam having to be coincidental with the line of the VRF are other explanations for the lack of accuracy of periapical radiographs (Hassan *et al.* 2009, Likubo *et al.* 2009, Kamburoğlu *et al.* 2010).

The slightly more favourable sensitivity results with CBCT were probably due to the ability to assess potential VRFs in different planes and at different angles. As would be expected the sensitivity increased with complete VRFs. However, it was still not in the same level of accuracy as reported in other studies (Hassan *et al.* 2009, 2010). A possible explanation for this is that both types of fractures in the present investigation were not as wide as those induced in the above mentioned studies, however, the widths of the fractures was not disclosed in these studies. Only in Özer's study was the width of VRFs measured, 2 sizes were compared 0.2mm and 0.4mm (Özer *et al.* 2010). Therefore these fractures were at least 2-4 times wider than the fractures created and assessed in the present study, this could account for the poor sensitivity of CBCT in the present study. It could be argued that the width of the fractures created by Özer *et al.* (2010) would have been detectable clinically and/or symptomatic therefore radiographic confirmation with CBCT would not have been required.

The overall poor specificity with CBCT was most probably due to streaking artefacts caused by the radiopaque root fillings (Katsumata *et al.* 2006, Zhang *et al.* 2007); this streaking mimics the appearance of a VRF. Several studies have concluded that the specificity appears to reduce with a gutta percha root filling (Hassan *et al.* 2009, Melo *et al.* 2010); and worse still with the increased radiodensity of gold posts (Melo *et al.* 2010). Wang *et al.* (2010) also found that the sensitivity of CBCT scanners was reduced in the presence of root filling materials (Wang *et al.* 2011). To overcome this it may be beneficial to use a root filling material with a lower radiopacity, thus reducing the scatter. At present there are no root fillings with a lower radiopacity, please refer to the patent application in Appendix II. Interestingly, the presence or absence of a root filling did not make a difference in the overall accuracy of the 4 of the 5 CBCT scanners assessed (Hassan *et al.* 2009b).

Hassan *et al.* (2009) found that the sensitivity (0.37) and specificity (0.95) of periapical radiographs for diagnosing VRFs in teeth that were instrumented but not obturated. Wang *et al.* (2011) found that sensitivity and specificity of periapical radiographs was 0.26 and 1.0, respectively. These results are in the same order of magnitude to those in the present investigation. However, their CBCT results showed a better sensitivity (0.79) and specificity (0.88) than the present investigation. Kamburoğlu *et al.* (2010) also found that CBCT was more accurate than periapical radiographs for assessing VRFs.

Hassan *et al.* (2009) used a hammer and chisel to create VRFs, while Kamburoğlu *et al.* (2010) also used a screw which was tapped into the root canal to induce fractures. However, in pilot studies using the same techniques mentioned in these studies it was not possible to consistently induce incomplete fractures of less than 150µm, instead the fractures were much wider (over 200µm) which would have made them instantly detectable. The creation of the fractures in this investigation was carried out using an Instron machine, the widths of incomplete fractures ranged from 50-110µm. This was in the same range as the fractures measured in the extracted root treated teeth diagnosed with VRF. The extractions were carried out as a traumatically as possible, using only luxators to elevate the roots out. However, there was no guarantee that the fractures measured were created whilst extracting these teeth. The widths of complete fractures were over 200µm.

The Instron® machine allowed a VRF to be induced in a controlled manner, i.e. firstly creating an incomplete VRF, after which a complete VRF could be created. Even with this technique, 7 out of 28 teeth had to be discarded as complete VRFs were inadvertently created before incomplete VRFs.

It is possible that the Hassan *et al.* and Kamburoğlu *et al.* techniques resulted in wider and therefore more readily detectable root fractures (Hassan *et al.* 2009a, Kamburoğlu *et al.* 2010), therefore increasing sensitivity, specificity and overall accuracy. The aim of the present investigation was to determine whether early 'hairline' fracture lines could be detected; these types of fractures commonly are not readily detectable with conventional radiographs (Rud & Omnell 1970, Chan *et al.* 1999, Youssefzadeh *et al.* 1999) and are less likely to be associated with deep periodontal probings and sinus tracts. Therefore, it was essential that true incomplete fractures could be induced, rather than reattaching completely fractured roots back together again to recreate incomplete VRFs.

The scanners used in the studies discussed above all varied; it is possible that specific scanners with their specific exposure parameters, voxel resolutions and detector sensitivity may also influence the detectability of VRFs (Hassan *et al.* 2009, 2010, Kamburoğlu *et al.* 2010, Wenzel *et al.* 2010). The low kV of the Accuitomo CBCT scanner used in the present may potentially result in better contrast. However, the low mA results in a lower signal to noise ratio resulting in poor ability to diagnose VRF. The number of basis projections, reconstruction parameters, machine specific artefacts may also contribute the variation in diagnostic ability (Hassan *et al.* 2010). A recent study assessing the accuracy of 5 different CBCT scanners of unobturated and obturated root canals with VRFs, revealed a difference in overall accuracy between the scanners (Hassan *et al.* 2010), the presence of a gutta-percha root filling also appeared to reduce the specificity of 4 of the 5 CBCT scanners assessed (including the Accuitomo scanner). Wenzel *et al.* (2010) has shown that high resolution settings resulted in improved accuracy for detecting VRF compared with low resolution settings for the iCat CBCT scanner; the low resolution setting had a similar level of accuracy as periapical radiographs. In addition the use of digital enhancement filters improved the accuracy of CBCT scans, however, the fractures assessed in this

study were in unobturated canals. These filters accentuate the transition in density levels, thus making subtle differences more distinct. Melo *et al.* (2011) found that sensitivity and specificity were influenced by voxel resolution; a 0.2mm voxel size was far more reliable than a 0.3mm voxel size which was found to be unreliable using the i-CAT® CBCT scanner.

In the present study only posterior extracted teeth were used and replanted into their respective sockets thus mimicking the clinical situation. The Hassan studies used a series of donor mandibles to house their extracted teeth, the resulting voids within the sockets were filled with soft tissue equivalent material (Hassan *et al.* 2009, 2010). If the sockets were filled with hard tissue equivalent or the teeth were extracted and replaced into their respective sockets then the attenuation profile may have reduced the accuracy of the reconstructed CBCT scans (Hassan *et al.* 2009, 2010). A similar methodology was used by Melo *et al.* (2010) with maxillary anterior teeth. In their study, the attenuation profile generated by the minimal nature of the anatomical noise (cortical plate) may also have influenced their results.

An *in-vivo* study would have been more realistic, however, presence or absence of a fracture could only be determined by extraction of the tooth in question and this would be unethical. The present investigation minimised variability in viewing conditions, and also tried to standardise VRFs, thus improving the validity of the results. Bernardes *et al.* compared the ability of periapical radiographs and CBCT to diagnose root treated teeth with clinical signs or symptoms of VRF (Bernardes *et al.* 2009). They concluded that CBCT was 'better than conventional radiography in the diagnosis of root fractures'. However, the presence or absence of VRF was not definitely determined, instead the reference standard used was the patient's symptomology and signs. In addition the associated peri-radicular bone loss adjacent to the VRF may have resulted in bias, as this bone loss rather

than an actual root fracture may have resulted in a positive diagnosis. A case series report of 3 teeth with VRF also concluded that CBCT was accurate at detecting VRF in both root treated and non-endodontically treated teeth 'especially when VRFs could not be confirmed by clinical findings and PRs (*periapical radiographs*)'. However, in all 3 cases, although subtle, there were clear clinical (for example, visible fracture) and/or radiographic signs (for example, periradicular bone loss) of VRF. The findings were just magnified with CBCT, VRF was confirmed by assessing the teeth after they had been extracted (Zou *et al.* 2011).

The poor inter- and intra-examiner agreement between examiners in the present investigation is a reflection of the inaccuracy of both radiographic systems in diagnosing VRF. This is not in agreement with the general trend in published studies which have reported a higher level of inter- and intra-examiner agreement (Hassan *et al.* 2009, 2010, Melo *et al.* 2010).

Artefacts are caused by discrepancies between the physical imaging process and the mathematical modelling, these artefacts may result in misdiagnosis. Various types of artefacts have been reported, these include beam hardening, scatter, extinction artefacts (Schulze *et al.* 2011). Beam hardening occurs when lower energy photons are absorbed by the radiodense object being assessed (in this case gutta percha) in preference to high energy photons. As a result, the remaining beam becomes 'harder' and more intense by the time it reaches the detector (Schulze *et al.* 2011). Therefore, the total energy of the beam is reduced behind the gutta percha, but the mean beam energy has increased. This results firstly, in distortion due to differential absorption, known as a *cupping artifact*, and secondly streaks and dark bands that can appear between two radiodense objects (Scarfe & Farman 2008). In addition the voxel resolution (0.125µm) was greater or equal to the width of the VRF being assessed, this resulted in a

phenomenon known as 'partial volume averaging' (Scarfe & Farman 2008, Wang *et al.* 2011) resulting in the inconsistent detection of the fractures being assessed. It has been reported that specific algorithms may be used to reduce the effects of artefacts (Tohnek *et al.* 2011).

Wang *et al.* (2011) reported a 26% reduction in sensitivity of CBCT to detect VRF in root treated teeth (0.71) compared with untreated teeth (0.97). They concluded that 'star-shaped streak artifacts' i.e. beam hardening compromised the quality of the images, thus 'decreasing the observers' confidence' therefore resulting in a reduced sensitivity.

3.5 Conclusion

This study indicates that periapical radiographs and CBCT are not accurate in detecting the presence and absence of simulated VRF. The imaging artefacts caused by the gutta percha root filling within the root canal most probably resulted in the over-estimation of VRF with CBCT, and also the overall inaccuracy of this system.

Despite the 3-dimensional nature of the reconstructed CBCT images, the poor resolution of CBCT, and artefacts caused by gutta percha contributed to the inaccuracy of CBCT.

Chapter 4

4. The radiographic periapical status of teeth treatment planned for primary endodontic treatment using digital periapical radiography and CBCT.

4.1 Introduction

Ideally, a diagnostic periapical radiograph will confirm the number of root canals, their configuration together with the presence or absence of periapical radiolucencies and their location (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008, Neelakantan *et al.* 2010). This important information not only helps confirm the endodontic diagnosis, but also aids treatment planning and management, and acts as a baseline for assessing the outcome of each unique endodontic problem.

As described in chapter 1, reconstructed CBCT views may be assessed accurately in any plane due to the isotropic nature of the voxels that make up the dataset. Thus setting the clinician free from the constraints of conventional radiographic imaging (Huomonen & Ørstavik 2004, Scarfe *et al.* 2008). This 3-dimensional assessment ultimately results in the number of roots, canals and periapical radiolucencies present in the tooth being significantly more perceptible to the clinician compared with periapical radiographs (Matherne *et al.* 2007, Paula-Silva *et al.* 2009b, Blattner *et al.* 2010). Not only can the presence of a periapical radiolucency be diagnosed with CBCT, but the specific root that it is associated with can also be confirmed (Rigolone *et al.* 2003, Gröndahl & Huomonen 2004).

Laboratory studies have confirmed that CBCT improves the detection of presence or absence of periapical radiolucencies when compared with periapical

radiographs (Chapter 2, Stavropolous *et al.* 2007, Özen *et al.* 2009). Clinical studies have generally focused on prevalence of periapical radiolucencies in teeth with failing root canal treatment (Lofthag-Hansen *et al.* 2007, Estrela *et al.* 2008, Low *et al.* 2008, Bornstein *et al.* 2011). There is a paucity of literature comparing periapical radiographs and CBCT scans for detecting periapical radiolucencies in untreated teeth diagnosed with endodontic disease.

The purpose of this clinical investigation was to compare the prevalence of periapical radiolucencies on individual roots of teeth viewed with periapical radiographs and CBCT of teeth treatment planned for primary root canal treatment.

4. 2 Materials and Methods

4.2.1 Subject material

Subjects included in this study were recruited from patients referred to the first author in a specialist endodontic practice for management of suspected endodontic problems. The patients were seen consecutively between 1st October 2008 and 30th April 2009. All patients were examined clinically; those with signs of gross caries, irreversible pulpitis and/or apical periodontitis of endodontic origin were advised of the diagnosis and their treatment options. Patients who consented to primary endodontic treatment were then considered for inclusion into the study. Exclusion criteria included: pregnant women, immunosuppressed patients, unrestorable teeth, and teeth with periodontal probing depths greater than 3 mm. There was no age limit for inclusion into the study. Approval was sought and granted by Guy's Research Ethics Committee, REC reference 08/H0804/17 (National Research Ethics Service, England), refer to appendix III.

One hundred and fifty-one teeth in 132 patients fulfilled the above criteria. These patients were asked to give their written consent to be involved in the study. A detailed verbal and written explanation of the purpose of the study was provided (appendix III).

Patients were also reassured that they did not have to volunteer to participate in this study, and that this would not have any bearing on how the treatment was carried out. Patients were also advised that all data would be treated confidentially. The storage and data management followed strict guidelines as laid down by the Research Ethics Committee of Guy's and St Thomas' Trust, London, UK.

4.2.2 Radiographic technique

The clinical examination included exposure of periapical radiographs using a beam aiming device to allow for standardisation of the radiographs. All radiographs were taken with a dental X-ray machine (Planmeca Prostyle Intra) using a digital CCD (Schick Technologies), the exposure parameters have already been described in chapter 2. The X-ray tube head, digital sensor and mandible were aligned to allow radiographs to be exposed using the paralleling technique. Small volume (40mm³) CBCT scans (3D Accuitomo F170, J Morita) with exposure parameters 90 kV, 5.0 mA and 17.5s were then taken of the area of interest. All CBCT scans were reformatted (0.125 slice intervals and 1.5 mm slice thickness).

4.2.3 Radiological assessment

The radiographic images were then assessed in 2 sessions as follows:

In session (1) the consensus panel assessed 50% of the periapical radiographs (n=76) followed by 50% of CBCT scans (n=76). In session (2) the consensus

panel assessed the remaining 50% of CBCT scans (n=77) followed by remaining 50% of periapical radiographs (n=77).

The radiographs and CBCT images for session 1 and 2 were randomly ordered in each session. CBCT images that best confirmed the presence or absence of a radiolucent periapical radiolucency in the sagittal, coronal and/or axial planes were used as the starting point for each root to be observed. In some cases the orientation of the teeth had to be changed to improve the visualisation of a periapical radiolucency, this was performed with One volume viewer (J Morita) software. These images were selected by an endodontist who was experienced in using CBCT in endodontic therapy. The consensus panel also had access to the whole CBCT scan using CBCT software (One-Volume viewer, J Morita) allowing them to scroll through any of the images. No further multiplanar reconstruction of the data (e.g. changing the orientation of the scan) was carried out. All images were assessed in a quiet, dimly lit room. The radiographs and CBCT images were viewed as a Keynote® presentation (Apple, Cupertino, CA, USA) on laptop computers (MacBook Pro®, Apple) which had a 15.5 inch LED backlit screen with a pixel resolution of 1680 x 1050. Sessions (1) and (2) were divided into two separate viewing periods over the course of a day to minimise the likelihood of consensus panel fatigue. There was at least a 1 week interval between each of the main sessions.

The consensus panel included 2 endodontists who already had clinical experience in using CBCT. They were trained using examples of clinical radiographs and CBCT images with and without the presence of periapical radiolucencies before embarking on the assessment. Before assessing the experimental material the reliability of each member of the panel was assessed by asking them each to grade 30 periapical radiographs and 30 CBCT images for the presence and absence of periapical radiolucencies. These radiographic

images were not from experimental sample. The examiners were not involved in assessing or treating the patients.

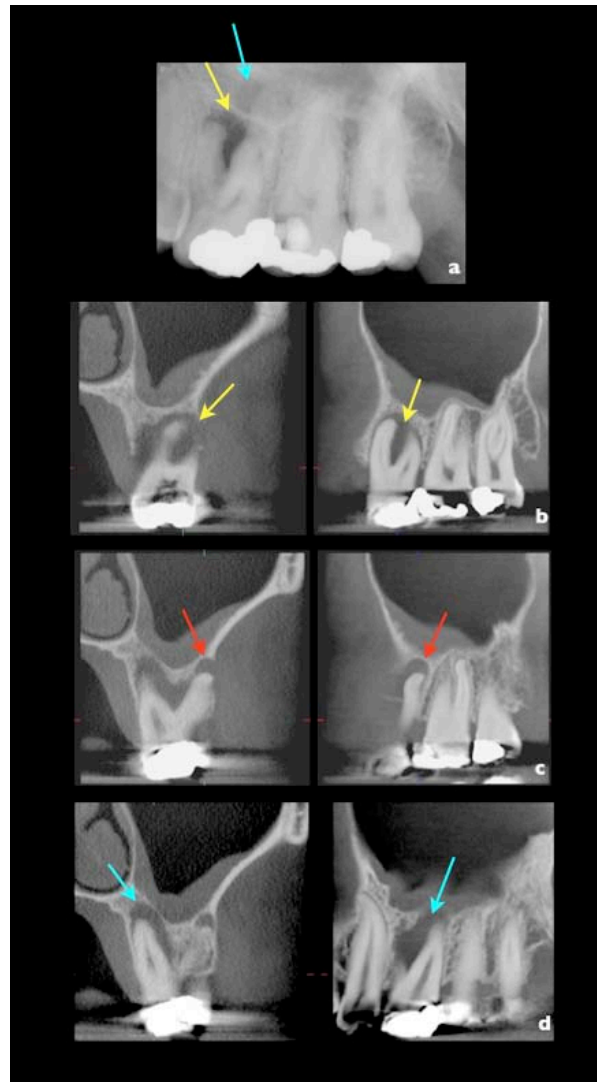


Figure 4.1 (a) Periapical radiograph of 26 reveals a periapical radiolucency associated with the mesio-buccal (yellow arrow) and palatal (turquoise arrow) root, (b-d) a series of coronal (left) and sagittal (right) reconstructed CBCT images reveal a periapical radiolucency associated with the (b) mesio-buccal, (c) disto-buccal-root (yellow arrow) and (d) palatal roots.

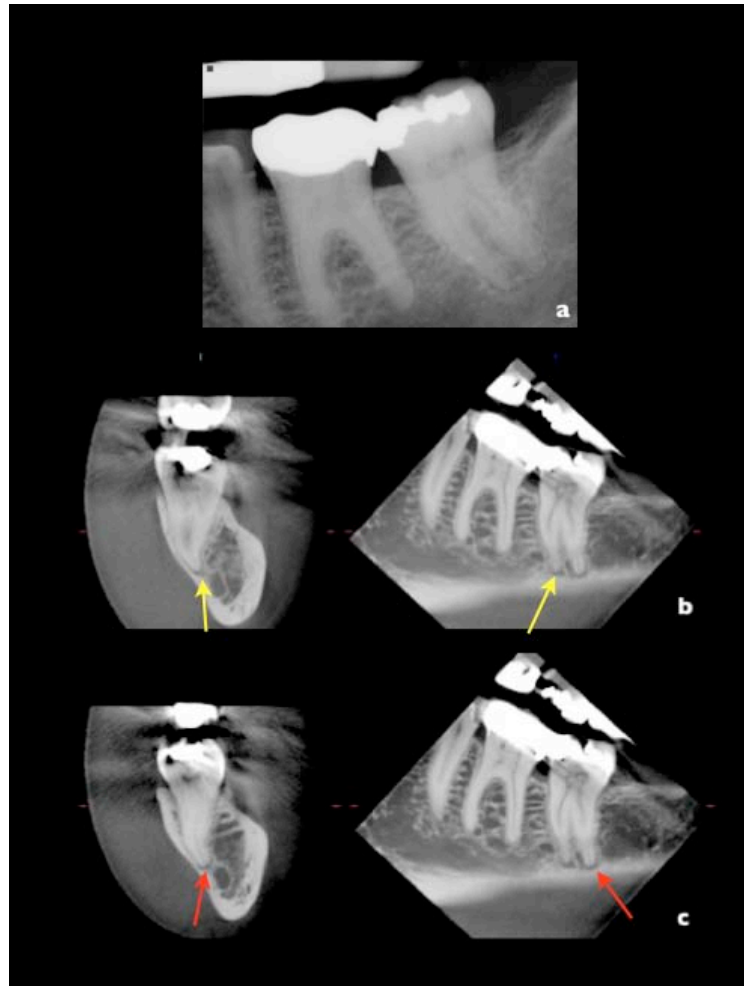


Figure 4.2. (a) Periapical radiograph of the 37 shows a healthy periapical tissues, (b-c) coronal (left) and sagittal (right) reconstructed CBCT images reveal periapical radiolucencies with the (b) mesial (yellow arrow) and (c) distal (red arrow) roots.

A periapical radiolucency was defined as a radiolucency associated with the radiographic apex of the root which was at least twice the width of the periodontal ligament space (Low *et al.* 2008, Bornstein *et al.* 2011). With multi-rooted teeth the presence or absence of a periapical radiolucency on each specific identifiable root was noted (figures 4.1-4.2). This allowed like-pairs of specific roots identified using periapical radiographs and CBCT to be assessed for the absence or presence of a periapical radiolucency. A consensus decision was reached for each of the radiographs and series of reconstructed CBCT images. An Excel (Excel 2010, Microsoft) spreadsheet was created to log data.

Each root was identified by number so that individual roots could be compared between radiological systems as pairs (table 4.1). It was expected that in some cases there would be a discrepancy in the number of roots being assessed between the 2 radiographic systems.

Tooth type	Root number		
	1	2	3
Incisors, canines, premolars*	Single root		
Premolars**	Buccal	Lingual/Palatal	
Mandibular molars	Buccal	Mesio-lingual	Distal
Maxillary molars	Mesio-buccal	Disto-buccal	Palatal

**premolar with a single root canal, **premolar with 2 root canals*

Table 4.1. Numbering of roots observed and identified during assessment.

4.2.3 Data analysis

Stata™ software (Stata 11) was used to analyse the data. The sample size was determined by assessing previous similar research. It was calculated that 150 teeth would provide 80% power to show a 25% difference in the number of radiolucencies identified as present between the radiological systems. Kappa analysis was used to assess the reproducibility of each of the 2 examiners of the consensus panel prior to the main study (Altman 1990). Comparison of periapical

radiographs and CBCT images for identification of presence and absence of radiolucencies was performed using McNemar tests on paired single roots per tooth. Assessment of the number of roots and periapical radiolucencies per tooth was described, but not statistically tested.

4.3 Results

One hundred and fifty-one teeth in 132 patients were assessed in this study. The mean age of the patients was 44.7 (standard deviation 13.7), and the percentage of females and males was 58% and 42% respectively.

The presence or absence of periapical radiolucencies was detected in 273 pairs of roots with both periapical radiographs and CBCT images. Comparison of the 273 paired roots revealed that periapical radiolucencies were present in 55 (20%) and absent in 218 (80%) roots when assessed with periapical radiographs. When the same 273 sets of roots were assessed with CBCT, radiolucencies were present in 130 (48%) and absent in 143 (52%) roots (table 3.2).

An additional 76 (22%) roots were identified with CBCT alone. Therefore, the total number of roots detected with a periapical radiolucency present was 138 (40%), and 211 (60%) of roots had no periapical radiolucency in the 349 roots identified with CBCT. Due to non-independence, this data was not analyzed statistically.

	X Ray	CBCT
Radiolucency absent	218 (79.9)	143 (52.4) 68*
Radiolucency present	55 (20.1)	130 (47.6) 8*

**Figures in italics refer to additional roots observed on CBCT scan but not on X ray*

Table 4.2. Shows the total number of roots (percentage) in the sample identified with and without a periapical radiolucency using both periapical radiography (X Ray) and CBCT. Due to non-independence, this data was not analysed statistically (n=273).

Tables 4.3-5.5 show the number of paired roots of teeth assessed for periapical radiolucencies in roots identified as 1, 2 and 3 respectively, using the schedule in Table 4.1. In all cases, CBCT images revealed a greater number of positive identifications than periapical radiographs ($p < 0.02$ to $p < 0.001$). Table 4.6 shows the agreement between the 2 radiographic systems for detecting the presence or absence of a periapical radiolucencies.

There was agreement on the absence of a periapical radiolucency between the 2 radiological systems in 50% roots where paired roots were visualized. When assessing for the presence of a periapical radiolucencies, there was agreement in 18% pairs of roots.

The Kappa values for inter-examiner agreement after the training session was 0.878 and 0.837 for periapical radiographs and CBCT images, respectively.

	X ray	CBCT
Radiolucency absent	107 (70.9)	68 (45.0)
Radiolucency present	44 (29.1)	83 (55.0)

Table 4.3. First set of paired single roots (percentage), i.e., root 1 as defined in table 4.1 identified with and without a periapical radiolucency using periapical radiography (X ray) and CBCT (n=151). In all cases, CBCT scan showed a greater number of positive identifications than x-ray ($p<0.02$ to $p<0.001$). McNemar test for paired data indicated increased positive identification by CBCT ($p<0.001$).

	X ray	CBCT
Radiolucency absent	83 (91.2)	53 (58.2)
Radiolucency present	8 (8.8)	38 (41.8)

Table 4.4. Second set of roots (percentage), i.e., root 2 as defined in table 1 identified with and without a periapical radiolucency using both periapical radiography and CBCT (n=91). McNemar test for paired data indicated increased positive identification by CBCT ($p<0.001$).

	X ray	CBCT
Radiolucency absent	28 (90.3)	22 (71.0)
Radiolucency present	3 (9.7)	9 (29.0)

Table 4.5. Third set of roots (percentage), i.e., root 3 as defined in table 1) identified with and without a periapical radiolucency using both periapical radiography and CBCT (n=31). McNemar test for paired data indicated increased positive identification by CBCT ($p<0.02$).

	PA (0) CBCT (0)	PA (1) CBCT (0)	PA (1) CBCT (1)	PA (0) CBCT (1)	paired roots
total paired roots	137	6	49	81	273
roots 1	64	4	40	43	151
roots 2	51	2	6	32	91
roots 3	22	0	3	6	31

Table 4.6. Breakdown of agreement of periapical radiolucencies (percentage) present (1) and absent (0) with periapical radiographs (PA) and CBCT.

4.4 Discussion

A reference standard to compare both radiological techniques would have been the ideal scenario. However, as this was a clinical study, this was not possible. The question arises: how valid were the diagnoses of the presence or absence of periapical radiolucencies using either radiographic technique? *Ex vivo* studies in which the detection of simulated (reference standard) periapical radiolucencies have been assessed with CBCT images and periapical radiographs have all confirmed the superior diagnostic ability of CBCT images over periapical radiographs (Chapter 2, Stavropoulos & Wenzel 2007, Özen *et al.* 2009, Soğur *et al.* 2012).

These findings have been reinforced by more recent *in vivo* dog studies (Paula-Silva *et al.* 2009b, 2009c). Intentionally created periapical radiolucencies were induced around the roots of dog's teeth by accessing the pulp chambers and leaving them exposed to the oral environment for 7 days (one group had vital pulps to serve as a positive control). After 180 days (one group was left untreated to serve as a negative control) periapical radiographs and CBCT scans were taken after which the animals were sacrificed and the root apices and surrounding periapical tissues were evaluated histologically (providing a reference standard). These studies confirmed that CBCT was not only more sensitive at detecting periapical radiolucencies, but also had a higher overall accuracy when compared to periapical radiographs. However, the validity of histology carried out in studies as described above is questionable as they are still 2 dimensional assessments of 3-dimensional periapical lesions and tissues.

The 2 examiners who constituted the consensus panel were experienced in interpreting CBCT data, as well as appreciating the limitations of this technology including its poorer resolution. Both examiners had used digital radiographs for at

least 5 years. A consensus panel has been used previously in studies assessing the detection ability of periapical radiolucencies to reduce inter-examiner variation (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008). Consensus panels surpass the accuracy of individual expert diagnoses where clinical information elicits diverse judgments. Several investigations have shown that inter-examiner agreement can be as little as 25% between examiners (Tewary *et al.* 2011), and one 'outlier examiner' can skew results (Goldman *et al.* 1971, Tewary *et al.* 2011). Viewing sessions were kept as short as practically possible, and all images were randomised both within, and between sessions to reduce the potential effect of examiner fatigue.

The differential detection rate of periapical radiolucencies with CBCT images compared with periapical radiographs has been shown to be in the same order of magnitude when 2 parallax radiographs (Lofthag-Hansen *et al.* 2007), or single periapical radiographs were taken (Low *et al.* 2009, Bornstein *et al.* 2011). Therefore, only one radiograph per tooth was included in this study. Soğur *et al.* (2012) has also found no statistical difference in the accuracy of detecting simulated periapical radiolucencies with one periapical radiograph versus 2 parallax radiographs. The merits of the dynamic nature of the digital periapical radiographic system have already been discussed in chapter 2. In addition, the effective dose for a digital periapical radiographic system is lower than for its film counterpart (Nair & Nair 2007). Other reported advantages of direct digital radiographs over filmed-based images include: instant images, easier storage and easier communication with colleagues and patients (Soh *et al.* 1993, Wenzel 2006). Studies comparing the ability of conventional films and digital sensors to detect periapical radiolucencies have found no difference between the radiographic systems (Folk *et al.* 1996, Mistak *et al.* 1998, Soğur *et al.* 2012).

Anti-glare LCD screens with a high pixel resolution were used to provide a high quality image for the assessment of radiographs and CBCT images. There is evidence to suggest that LCD and high resolution cathode ray tubes are equally effective for assessing CBCT images and digital radiographs (Baksi *et al.* 2009).

In this study periapical radiographs and reconstructed CBCT images were assessed for their diagnostic ability in detecting radiographic signs of periapical periodontitis in 151 teeth planned for primary root canal treatment. Previous clinical studies have tended to focus on teeth which have already been root filled. In the study conducted by Lofthag-Hansen *et al.* (2007), 42 (91%) of the 46 teeth assessed with signs of endodontic disease had already been root filled. In 2 other studies, all the teeth had been root filled (Low *et al.* 2008, Bornstein *et al.* 2011). These studies focused on either posterior teeth (Lofthag-Hansen *et al.* 2007), maxillary posterior teeth (Low *et al.* 2008), or mandibular teeth alone (Bornstein *et al.* 2011).

The results of the present study revealed that periapical radiolucencies were detected in only 55 (20%) of roots with periapical radiographs compared to 130 (48%) of roots with CBCT images. That is, over twice as many periapical radiolucencies were detected with CBCT images when paired roots were compared. Periapical radiolucencies were absent in 80% and 52% of paired roots assessed with periapical radiographs and CBCT images, respectively. In addition 76 (22) roots were identified only with CBCT images; periapical radiolucencies were present in 8 (11%) of these roots and absent in 68 (90%). These results concur with previous studies; Lofthag-Hansen *et al.* (2007) compared the prevalence of periapical periodontitis in 46 maxillary and mandibular posterior teeth, and concluded that 20% more teeth had periapical radiolucencies when assessed with CBCT images reconstructed images compared with periapical radiographs. Low *et al.* (2008) found that 34% more teeth had associated

periapical radiolucencies with reconstructed CBCT images than with periapical radiography in 74 posterior maxillary teeth referred for periapical microsurgery. Estrela *et al.* (2008) assessed 83 untreated teeth diagnosed with an endodontic problem, and found the prevalence of radiological signs of periapical periodontitis with periapical radiographs and CBCT images reconstructed images was 36% and 75% respectively, a 39% difference. Interestingly, the prevalence of periapical periodontitis was even lower with panoramic radiographs at only 22%. None of these studies specifically assessed paired roots.

One important question to be addressed is the potential presence of false positives in the CBCT images. Perhaps the ideal test would be to compare reconstructed CBCT images of periapical tissues to histologic assessment in humans, however, this is impossible as it is unethical to carry out such an investigation. As stated earlier the validity of histological assessment is questionable. If histological comparisons were to be made, then it would be desirable to perform serial sectioning (Nair *et al.* 1996), thus allowing comparative analysis of CBCT and histological slices, to date this has not been explored. Due to cross infection control regulations, it would also not be possible to undertake a similar study on human cadavers. However, previous *ex-vivo* and *in-vivo* studies also found a higher negative predictive value for CBCT images compared to periapical radiographs (refer to the results of chapter 2, Paula-Silva *et al.* 2009c).

Bornstein *et al.* (2011) found that there was a 74% agreement between periapical radiographs and CBCT images for the presence of a periapical radiolucency on paired roots of mandibular molar teeth. Although they did not compare paired roots, Low *et al.* (2008) found that there was 66% agreement between periapical radiographs and CBCT images for presence of a periapical radiolucency. In the present study there was only a 17.9% agreement between the radiological

systems for the detection of the presence of a periapical radiolucency. The higher agreement in the previously published studies may be due to the fact that the teeth considered for inclusion in these studies had clinical and/or radiological signs of failed existing endodontic treatment. Therefore, the likelihood of a periapical radiolucency being detected would naturally be higher. In the present study all teeth were untreated, and consisted of teeth with vital (e.g. gross caries, irreversible pulpitis) as well as infected necrotic pulps (e.g. chronic periapical periodontitis). In this study 59 (39%) teeth were diagnosed to have irreversible pulpitis after clinical and conventional radiographic examination (i.e. no signs of a periapical radiolucency), however, 26 (44%) of these teeth had periapical radiolucencies when assessed with CBCT images. The presence of periapical radiolucency(s) detected only by CBCT images changes the endodontic diagnosis to chronic periapical periodontitis, and this may change treatment strategy. For example, a multiple visit treatment with calcium hydroxide dressing inter-appointment rather than single visit treatment. It may also potentially change the prognosis of the treatment, in which case the patient needs to be informed (Ng *et al.* 2011).

The detection of periapical radiolucencies using CBCT images will also help the clinician in avoiding direct or indirect pulp capping procedures on teeth which appear to have pulps with reversible pulpitis (i.e. respond positively to vitality testing and show no periapical radiolucencies with periapical radiographs).

As reported in chapter 2, the higher prevalence of periapical radiolucencies detected by CBCT images is a result of the 3-dimensional assessment of the teeth and surrounding tissues. Thus allowing slices of data to be reconstructed without the overlying anatomical noise (i.e. cortical plate, zygomatic buttress and/or superimposed roots) obscuring the area of interest and therefore the status of the periapical tissues could be assessed. Slice angles were selected so that the

coronal and sagittal views were parallel to the root being assessed, thus minimising any distortion. These factors ultimately resulted in the presence or absence of periapical radiolucencies being significantly more perceptible with CBCT images than with periapical radiographs. This is also why more roots could be assessed with CBCT images (Özen *et al.* 2009, Patel *et al.* 2009a, Paula-Silva *et al.* 2009a). The lower prevalence of periapical radiolucencies with periapical radiography was due the combination of anatomical noise, geometric distortion and the 2-dimensional nature of the image produced (Estrela *et al.* 2008, Matherne *et al.* 2008, Paula-Silva *et al.* 2009b).

Each endodontic problem assessed in the present study was unique, therefore the nature and location of the periapical radiolucencies varied from case to case. However, it was considered important to carry out a clinical study, as the mechanically 'machined' periapical radiolucencies used in previous *ex vivo* studies (chapter 2), although standardised, do not truly reflect the nature of real periapical radiolucencies, which are generally irregularly shaped cavities. In this study the CBCT scans not only aided diagnosis, but facilitated the overall management of each case, for example, the presence and location of root canals, could be determined before treatment commenced (Tu *et al.* 2009, Neelakantan *et al.* 2011). Therefore, the endodontist will know exactly where to look with the aid of the dental operating microscope, therefore reducing the time 'exploring' the pulp chamber looking for canal entrances.

At present CBCT is typically used to help diagnose poorly localised endodontic problems (for example, irreversible pulpitis) and/or to treatment plan complex endodontic problems, for example, multi-rooted teeth (Patel 2009, Pigg *et al.* 2011). In addition to revealing the true status of the periapical tissues, CBCT also provides other clinically relevant information which cannot be readily elicited from periapical radiographs such as the number and configuration of root canals,

proximity of adjacent neighbouring anatomical structures and cortical plate topography (Rigolone *et al.* 2003, Estrela *et al.* 2008b, Low *et al.* 2008, Matherne *et al.* 2008).

4.5 Conclusion

This study revealed that periapical radiolucencies were detected in only 55 (20%) of paired roots with periapical radiographs compared to 130 (48%) with CBCT images, i.e over twice as many periapical radiolucencies were detected with CBCT when paired roots were compared.

In view of the superior accuracy of CBCT compared with periapical radiographs for diagnosing the radiographic manifestations of periapical periodontitis it may be time to review the way that both epidemiological and outcome studies are performed as CBCT data offers a more accurate objective baseline value which has the potential to reduce false negatives so often detected with periapical radiographs.

Chapter 5

5 Radiographic outcome of primary endodontic treatment assessed with CBCT and digital periapical radiography.

5.1 Introduction

The diagnostic outcome of endodontic treatment is based on clinical and radiological findings (Friedman *et al.* 2003, Ng *et al.* 2011). It is not uncommon for post-endodontic treatment disease to be clinically asymptomatic (Kirkevang & Hørsted-Bindlev 2002, Huumonen & Ørstavik 2002, Wu *et al.* 2009), therefore radiological assessment is essential to objectively determine the outcome of treatment.

The results from outcome studies allow the clinician to estimate the prognosis of the proposed endodontic treatment. This can then be compared to the prognosis of possible alternative treatment strategies (for example, single implant-crown restorations); this essential information along with the benefits and risks of the various treatment options allows the patient to choose the most suitable treatment option for their individual needs (Friedman 2003).

Periapical radiography is the technique of choice for assessing every stage of endodontic treatment; diagnosing, managing and assessing the outcome (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008, Patel *et al.* 2009a). A periapical radiolucency represents a reduction in the mineral density of the affected periapical bone in response to a localised inflammatory reaction to residual and/or re-infection within the root canal system (Bender 1982, Ørstavik & Larheim 2008). Conversely, the absence of a periapical radiolucency at the periapex of the endodontically treated root indicates the absence of periapical periodontitis, suggesting that endodontic treatment has been successful (Strindberg 1956,

European Society of Endodontology 2006). This is the basis of how both non-surgical and surgical endodontic treatments have been assessed for nearly 90 years (Blayney 1922, Peters & Wesselink 2002, Friedman *et al.* 2003, Chong *et al.* 2003, Chivigny *et al.* 2008).

Ex-vivo and *in-vivo* studies have confirmed that periapical radiography is of limited use for detecting periapical radiolucencies (Bender & Seltzer 1961, Bender 1997, Jorge *et al.* 2008, Paula-Silva *et al.* 2009b). As discussed in chapter 2, periapical radiolucencies are usually only diagnosed when there has been perforation or erosion of the overlying cortical plate (Seltzer & Bender 1961, Jorge *et al.* 2008). The 2-dimensional nature of radiographs means that they cannot consistently reveal the true nature or location of a periapical radiolucency (Van Vorde & Bjorndahl 1969, Forsberg & Halse 1994).

Several studies have been published confirming the improved diagnostic accuracy of CBCT over periapical radiography for diagnosing periapical radiolucencies (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008, Estrela *et al.* 2008a, Bornstein *et al.* 2011). Recently, Paula-Silva *et al.* assessed the diagnostic outcome of endodontic treatment performed in dogs using periapical radiographs and CBCT, they concluded that the treatment outcome varied according to the radiological system used; a favourable outcome was 79% and 35% with periapical radiographs and CBCT, respectively (Paula-Silva *et al.* 2009b). Small field of view scans are best suited for diagnosing and managing of endodontic problems (Patel 2009, SedendexCT 2011). To date, there have been no published studies comparing the diagnostic outcome of endodontic treatment in humans using pre-diagnostic and follow-up with periapical radiographs and CBCT.

The purpose of this study was to determine the radiographic change in periapical status of individual roots with periapical radiographs and CBCT 1 year after primary root canal treatment treatment, and to determine a radiological outcome of treatment for each tooth.

5.2 Materials and Methods

5.2.1. Subject material

The subject material consisted of the patients data collected from the investigation described in chapter 4. All patients were advised that the diagnostic phase and treatment protocol were regularly used, and that the only difference to conventional treatment and follow-up was that a diagnostic and 1 year follow-up CBCT scan would also be taken.

5.2.2 Radiographic technique

The pre-operative and 1 year follow-up assessment included exposure of periapical radiographs using a beam aiming device to allow for standardisation of the radiograph. All radiographs and CBCT scans were taken using the same protocol as described in described in chapter 4.

The brightness and contrast of all the acquired images was enhanced to improve visualisation of the periapical radiolucenices. All CBCT data was reformatted (0.125 slice intervals and 1.5 mm slice thickness).

5.2.3 Root canal treatment procedure

All root canal treatments were carried out by a single operator (SP) in a single visit. The tooth to be treated was anaesthetised and isolated under rubber dam. Before starting primary endodontic treatment, plaque deposits, calculus, caries and existing restorations were carefully removed after which the restorability of

the underlying tooth structure was assessed. Once the restorations had been removed the root canal system was accessed. In instances where minimal tooth structure was left, the tooth was restored with a glass ionomer (Fuji IX glass ionomer cement, GC America Alsip, Illinois, USA) foundation to allow good isolation with rubber dam.

All root canal treatments were performed using sterilised, single use endodontic files. A standardised protocol was used to disinfect and obturate the root canal system. Each canal was initially negotiated with size 08 and 10 stainless steel Flexofiles® (Dentsply Maillefer). The balanced force instrumentation technique was used to negotiate each canal to its provisional working length. The definitive working length was determined with the aid of an apex locator (Root ZX II, J Morita) in conjunction with measurements using the CBCT software (I-Dixel, J Morita). The working length was always calculated as 1mm short of the '0' apex locator reading length. Canals were then prepared to at least a size 20 Flexofile® to the working length, after which ProTaper nickel-titanium rotary instruments (Dentsply-Maillefer) at 300RPM were used in a crown-down approach to prepare each root canal to at least a F1 master apical rotary file. Canals were continuously irrigated with sodium hypochlorite (Chlorax 2%) for 30 minutes. The irrigant was replenished every 3-4 minutes after which it was immediately agitated with an appropriately selected gutta percha point extending to 2mm short of the working length for approximately 30 seconds. The root canals were then irrigated with 15% ethylene diaminetetraacetic acid (EDTA) (ENDO-Solution, CerKamed) followed by a final irrigation with sodium hypochlorite. For the EDTA and final sodium hypochlorite rinses the irrigant was energised with a size 25 Endo-activator (Dentsply Maillefer) for 1 minute which was placed 2-3 mm short of the working length. The canals were then dried with paper points and obturated with gutta percha and AH sealer (Dentsply Maillefer) using a warm vertical compaction technique. The teeth were restored with permanent glass ionomer

cores (Fuji IX glass ionomer cement) or composite resin (Herculite ultra, Kerr, Orange, CA, USA) depending on the referring practitioners preference.

A dental operating microscope was used during treatment, and all teeth requiring permanent, cuspal-coverage restorations were restored by the referring practitioner within 1 month of completion of the endodontic treatment.

5.2.4 Follow-up assessment

All patients were contacted approximately 11 months later to schedule a 12 month review appointment. Clinical assessment included assessing the tooth for tenderness to percussion, mobility, and checking for increased periodontal probing depths. The soft tissues were also assessed for tenderness to palpation, signs of erythema and sinuses. The integrity and marginal fit of the definitive restoration were also assessed. Periapical and CBCT radiographic assessment was carried out as described previously in chapter 4.

Assessment of the data was carried out by the same consensus panel described in chapter 4. Several months had elapsed between the assessment of radiographic images in chapter 4 and 5, therefore the examiners were retrained using 50 examples of periapical radiographs, and 50 CBCT reconstructed images with and without the presence of periapical radiolucencies before embarking on the assessment. Before assessing the experimental material, the agreement of each member of the panel (i.e. inter-examiner agreement of the 2 examiners of the consensus panel) was assessed by asking them to grade the outcome of endodontic treatment of 20 cases using periapical radiographs and 20 cases using series of reconstructed CBCT mages. The radiographs and CBCT datasets were viewed as Keynote presentations (Apple) on laptop computers (MacBook Pro, Apple) as described in chapter 4.

The radiographic diagnostic outcome of each root was classified in 6 categories:

- 1-new periapical radiolucency
- 2-enlarged periapical radiolucency
- 3-unchanged periapical radiolucency
- 4-reduced periapical radiolucency
- 5-resolved periapical radiolucency
- 6-unchanged healthy periapical status (no radiolucency before and after treatment)

For the purposes of clinically defined outcomes, a 'healed' outcome (i.e. strict criterion) was defined where a periapical radiolucency was absent (outcome 5 & 6), and a 'healing' outcome (i.e. loose criterion) included a radiolucency which had reduced in size or was absent (outcome 4 - 6).

A periapical radiolucency was defined as a radiolucency associated with the radiographic apex of the root which was at least twice the width of the periodontal ligament space as described in previous studies (Low *et al.* 2008, Bornstein *et al.* 2011). With multi-rooted teeth the presence or absence of a periapical radiolucency on each identifiable root was noted (Table 5.1). This allowed the outcome of root canal treatment to be determined for specific roots using periapical radiographs and reconstructed CBCT images (Figures 5.1-5.4).

In multi-rooted teeth the diagnostic outcome for the tooth was assessed by using the root with the 'worst' diagnostic outcome category, whilst for single rooted teeth the diagnostic outcome category for the root was also used for tooth outcome. In the event of multi-rooted teeth with the periapical status of one root classified as 'category 1' and the other root classified as 'category 2', the category 1 was considered the 'worst case' scenario. All data was anonymised. A series of up to 10 reconstructed CBCT images that best confirmed the presence

or absence of one or more periapical radiolucencies in the sagittal, coronal and/or axial planes was used as the starting point for each tooth observation. The consensus panel also had access to the raw CBCT data using CBCT software (one-Volume viewer, J Morita) allowing them to scroll through any of the orthogonal scans. All images were assessed in a quiet dimly lit room. All CBCT datasets were assessed using the same computer monitor(s).

*premolar with a single root canal, **premolar with 2 root canals

Tooth type	Root number		
	1	2	3
Incisors, canines, premolars*	Single root		
Premolars**	Buccal	Lingual/Palatal	
Mandibular molars	Buccal	Mesio-lingual	Distal
Maxillary molars	Mesio-buccal	Disto-buccal	Palatal

Table 5.1. Numbering of roots observed and identified during assessment.



Figure 5.1 (a) pre-operative radiograph of 26 revealing periapical radiolucencies on mesio-buccal (turquoise arrow) and palatal (red arrow) root, (b) 1 year follow-up radiograph reveals a significant reduction in size of the periapical radiolucency on the mesio-buccal root (outcome 4), complete resolution of periapical radiolucency on the palatal root (outcome 5), and no change in the healthy periapical status of the distobuccal root (outcome 6). (c-h) reconstructed CBCT images reveal pre-operative periapical radiolucencies on mesio-buccal, disto-buccal (yellow arrow) and palatal roots, which 1 year later have reduced in size on the mesio-buccal and disto-buccal roots (outcome 4), and has resolved (outcome 5) on the palatal root. Radiographic and CBCT tooth outcome is 5 and 4 respectively.

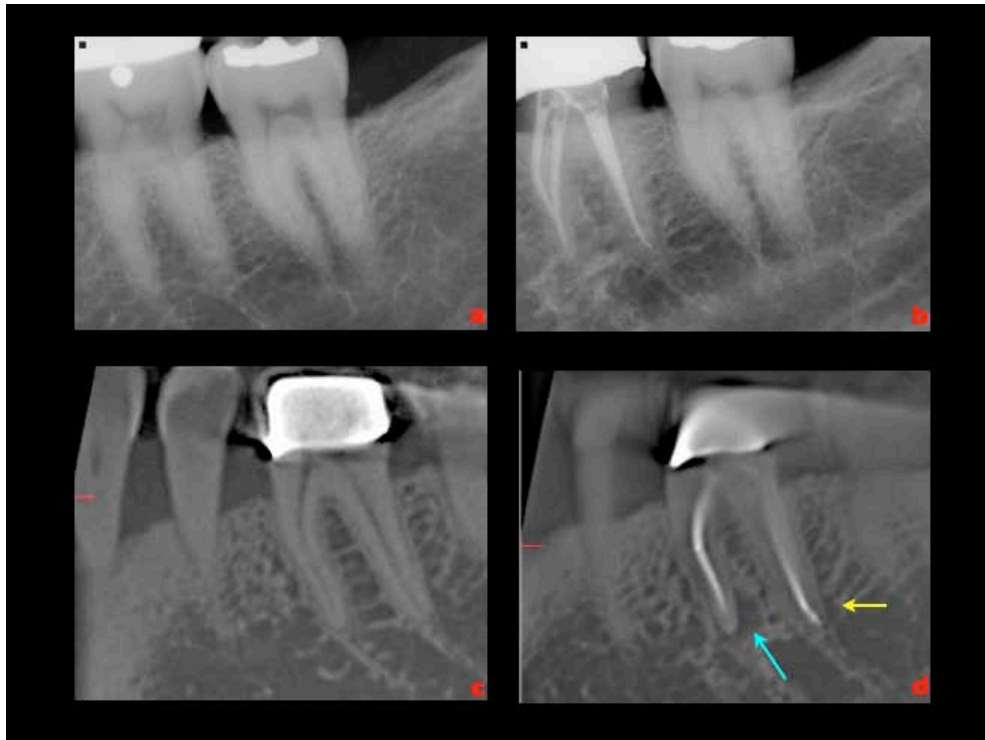


Figure 5.2 (a) pre-operative radiograph of 36 and, (b) 1 year follow-up radiograph revealing healthy periapical tissues for both roots (outcome 6). Figures (c-d) reconstructed CBCT images reveal the no pre-operative periapical radiolucencies on either the mesial (turquoise arrow) or distal (yellow arrow) roots, but 1 year later there are new periapical radiolucencies on both roots (outcome 1). Radiographic and CBCT tooth outcome is 6 and 1 respectively.

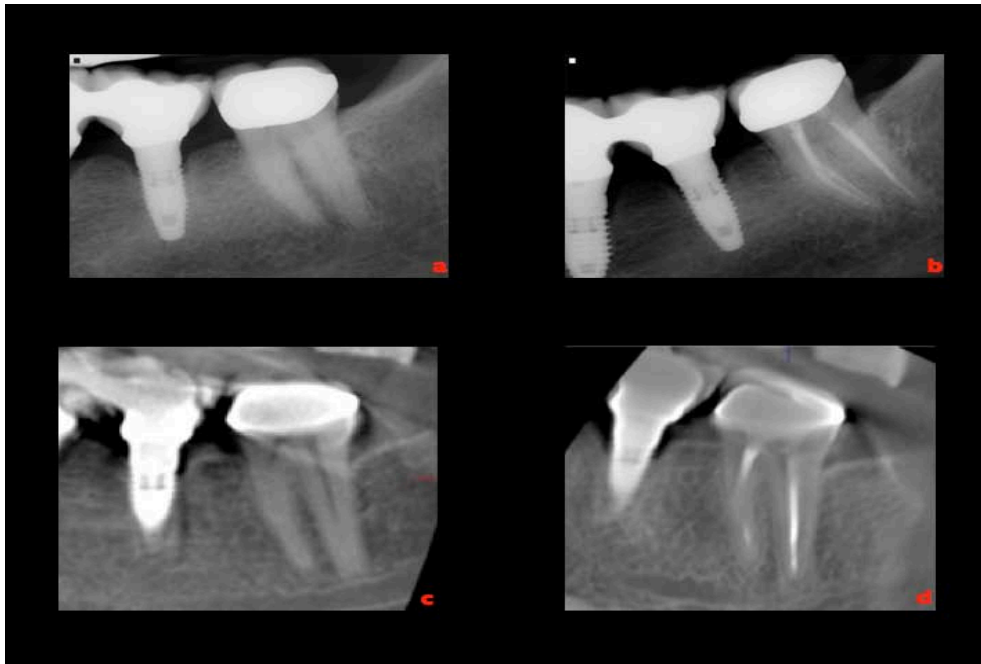


Figure 5.3 (a) pre-operative radiograph of 37 and, (b) 1 year follow-up radiograph revealing healthy periapical tissues (outcome 6 for both roots). Figures (c-d) reconstructed CBCT images reveal no periapical radiolucencies on either the mesial or distal roots, both pre-operatively and at 1 year recall (outcome 6). Radiographic and CBCT tooth outcome is 6.

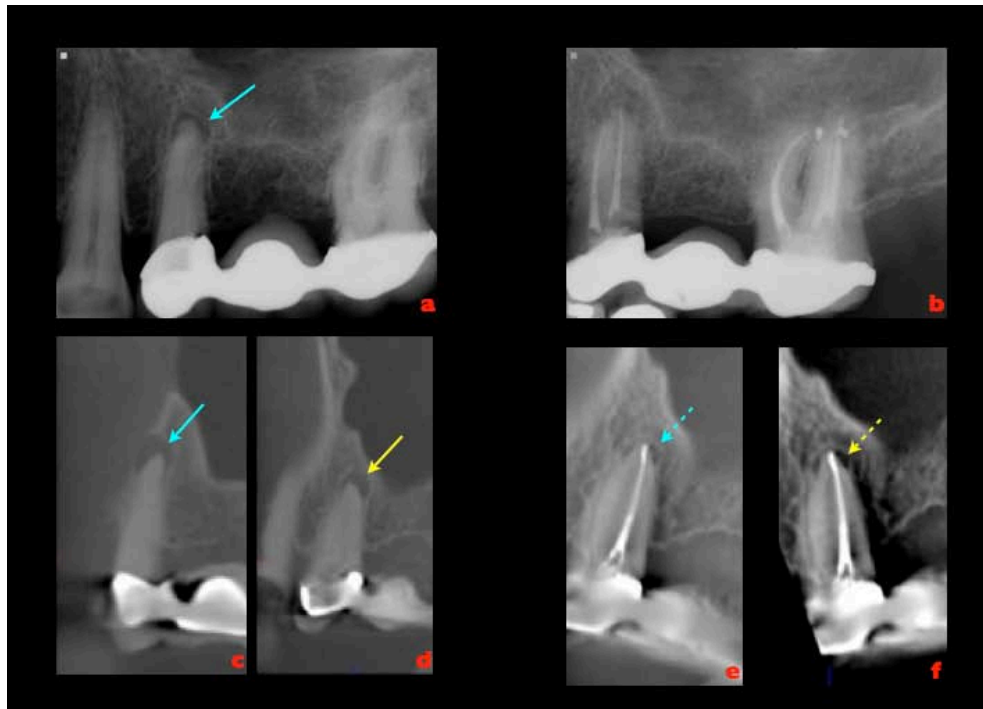


Figure 5.4 (a) Pre-operative periapical radiograph of 24 revealing periapical radiolucencies on the buccal and palatal (turquoise arrow) roots, (b) 1 year follow-up radiograph reveals complete resolution of periapical radiolucencies (outcome 5). (c-d) reconstructed CBCT images reveal pre-operative periapical radiolucencies on the buccal (turquoise arrow) and palatal (yellow arrow) roots which 1 year later have completely resolved, shown with respective broken arrows (outcome 5). Radiographic and CBCT tooth outcome is 5.

5.2.5 Assessment of experimental data

The experimental material was assessed in 3 sessions as follows:

In the first session, the consensus panel assessed 50% of the periapical radiographs (n=61) followed by 50% of CBCT reconstructed images (n=62); in the second session, the consensus panel assessed the remaining 50% of CBCT reconstructed images (n=61) followed by the remaining 50% of periapical radiographs (n=62). Periapical radiographs and CBCT images of the same tooth were not assessed in the same session; in the third session 70 periapical radiographs and 70 series of CBCT images were assessed to determine intra-consensus panel agreement.

The radiographic images were assessed as described in the calibration session. There was at least a one week interval between each session, and the images within each session were randomly ordered. The pre-operative and the 1 year follow-up periapical radiographs of each case were viewed together to allow the examiners to assess the images for the presence, absence or change (increase/decrease) in size of an existing periapical lesion. This was also done when the CBCT reconstructed images were assessed. The first and second sessions were divided into at least three separate viewing periods over the course of a day to minimise the likelihood of consensus panel fatigue. The periapical tissue status category 5 and 6 were given when there was an intact lamina dura with a maximum widening of 2mm immediately adjacent to any flush or extruded root filling material.

5.2.6 Data analysis

Data were analysed using Stata™ software (Stata 11). Kappa analysis was used to assess the inter-examiner agreement prior to the main study and the intra-consensus panel agreement during the study. Comparison of periapical radiographs and reconstructed CBCT images for diagnosis of outcome by individual roots and by tooth was performed using the generalized McNemar's or Stuart-Maxwell test of symmetry for testing marginal homogeneity with multiple paired categories. Comparison of systems for 'healed' and/or 'healing' outcomes was performed using the exact McNemar test.

Comparison of diagnostic outcome by tooth type within and between radiographic systems was performed using chi-square tests. Anterior teeth included incisors and canines; posterior teeth included premolar and molar teeth. Where multiple contrasts were performed on the same data set, as with the comparison of anterior/posterior and maxillary/mandibular sites, the p value for statistical significance was adjusted ($p < 0.01$). Otherwise, $p < 0.05$ was accepted as indicating statistical significance.

5.3 Results

5.3.1 Patient data

Ninety-nine of the original 132 patients from part 1 of this study were reviewed (75% recall rate), this included 123 teeth (Figure 5 & 6) of the original 151 teeth initially treated (82%). The percentage of females and males was 58% and 42%, respectively. The mean age of the patients was 44.5 years (standard deviation 13.7) and ranged from 9-76 years of age.

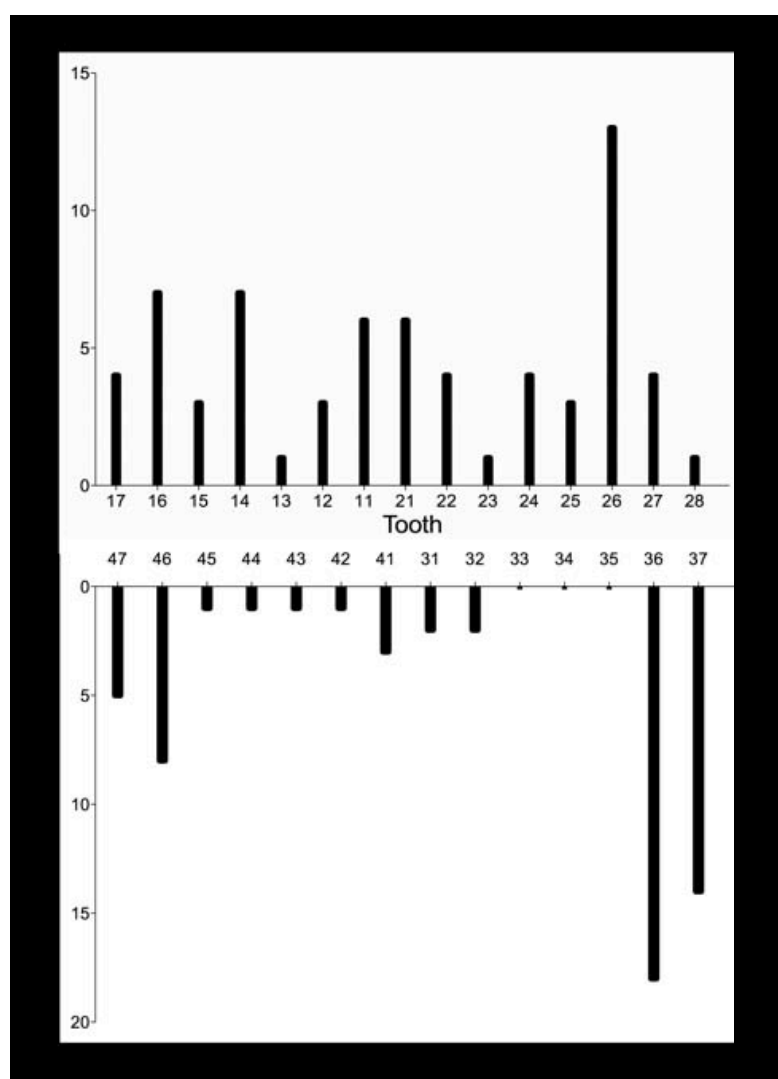


Figure 5.5. Frequency distribution of teeth (n=123) assessed 1 year post-root canal treatment.

5.3.2 Kappa analysis

Kappa analysis carried out before embarking on assessing the experimental material revealed a good inter-examiner agreement for periapical radiographs (0.837) and CBCT (1.000) for root 1, but less so for roots 2 and 3 (Table 5.2). Kappa values for the intra-consensus panel agreement ranged from 0.736 to 0.776 for periapical radiographs, and between 0.858 and 0.916 for CBCT (Table 5.3).

System	Root 1	Root 2	Root 3
X ray	0.837 (0.813-0.919)	0.440 (0.155-1.000)	*
CBCT	1.000 (1.000-1.000)	0.726 (0.634-1.000)	0.588 (0.093- 1.000)

Table 5.2 Kappa values (95% confidence intervals) for pre-study inter-examiner agreement on outcome diagnosis using periapical radiography (X ray) and cone beam computed tomography (CBCT) (n=20). * too few values for analysis.

System	Root1	Root2	Root3
X ray	0.768 (0.651-0.886)	0.736 (0.403-0.856)	0.776 (0.750-0.857)
CBCT	0.915 (0.879-0.980)	0.916 (0.915-0.959)	0.858 (0.821-1.000)

Table 5.3 Kappa values (95% confidence intervals) for intra-consensus panel agreement on outcome diagnosis using periapical radiographs (X ray) and cone beam computed tomography (CBCT) one week apart (n=70).

5.3.3 Clinical Assessment

None of the patients presented with any symptoms 1 year post-treatment, and they all confirmed that they were not avoiding masticating with the root treated tooth (i.e. the root treated tooth was functional). Clinical examination of all the teeth and the surrounding tissues was unremarkable, and all coronal seals were intact.

5.3.4 Analysis by root

A statistically significant difference in outcome diagnosis of single roots was observed between periapical radiographs and CBCT in roots 1 and 2 ($p=0.031$ and $p<0.001$ respectively). The difference for root 3 did not reach statistical significance ($p=0.125$). Overall, for all roots, the 'healed' rate was 92.7% for periapical radiographs and 73.9% for CBCT ($p<0.001$), whilst the combined 'healed' and 'healing' rate was 97.2% and 89.4%, respectively ($p<0.001$) (Tables 5.4 & 5.5). The combined prevalence of new or increased sized periapical radiolucencies was 0.9% and 8.3% using periapical radiographs and CBCT, respectively. This difference approached statistical significance ($p=0.077$).

Outcome	Root 1		Root 2		Root 3		Total 1+2+3	
	X ray	CBCT	X ray	CBCT	X ray	CBCT	X ray	CBCT
1 - new lesion	0	7	1	4	0	1	1	12
2 - enlarged lesion	0	5	0	1	1	0	1	6
3 - unchanged lesion	4	5	0	0	0	0	4	5
4 - reduced lesion	10	22	0	9	0	3	10	34
5 - resolved lesion	28	31	9	16	1	3	38	50
6 -no lesion before/after treatment	81	53	60	40	23	18	164	111
Total	123	123	70	70	25	25	218	218

Outcome of each tooth was assessed using the following criteria: 1-new lesion, 2-enlarged lesion, 3-unchanged lesion, 4-reduced lesion, 5-resolved lesion, 6-no lesion before or after treatment.

Table 5.4 Frequency distribution of each periapical outcome of endodontic treatment for paired roots assessed using periapical radiographs (X ray) and CBCT.

	Root 1		Root 2		Root 3		Total 1+2+3	
	X ray	CBCT	X ray	CBCT	X ray	CBCT	X ray	CBCT
1/2/3 - failed	3.3	13.8	1.4	7.1	4	4	2.8	10.6
1/2 - new/larger lesions	0	9.8	1.4	7.1	4	4	0.9	8.3
3 - no change in size	3.2	4.1	0	0	0	0	1.8	2.3
4/5/6 - healed/healing (includes healed)	96.7	86.2	98.6	92.9	96	96	97.2	89.4
4 - healing	8.1	17.9	0	12.9	0	12	4.6	15.5
5 - healed	22.8	25.2	13.7	22.9	4	12	17.4	23.0
5/6 - healed	88.6	68.3	98.6	80	96	84	92.7	73.9

Outcome of each tooth was assessed using the following criteria: 1-new lesion, 2-enlarged lesion, 3-unchanged lesion, 4-reduced lesion, 5-resolved lesion, 6-no lesion before or after treatment.

Table 5.5 Percentage of combined outcomes indicating healing, no change or failure for individual roots (data derived from table 5.4) assessed with periapical radiographs (X ray) and CBCT.

5.3.5 Analysis by tooth

A statistically significant difference in outcome diagnosis of teeth was observed between periapical radiograph and CBCT ($p < 0.001$). The 'healed' rate was 87% for periapical radiographs and 62.5% for CBCT ($p < 0.001$), whilst the combined 'healed' and 'healing' rate was 95.1% and 84.5%, respectively ($p = 0.002$) (Table 5.6a). The combined prevalence of new and increased size periapical radiolucencies was 1.6% and 11.4% with periapical radiographs and reconstructed CBCT images respectively ($p < 0.001$).

Teeth with no pre-treatment periapical radiolucencies (Table 5.6b) showed fewer failures (1.3%) with periapical radiographs compared with reconstructed CBCT images (17.6%). This difference was statistically significant ($p < 0.001$). Table 5.6c shows the combined prevalence of enlarged and unchanged periapical radiolucencies was 10.4% for periapical radiographs and 13.9% for reconstructed CBCT images. This difference was not statistically significant ($p = 0.652$).

Comparison within both radiographic systems revealed statistically significant differences in outcome diagnoses by tooth group for both periapical radiographs ($p = 0.002$) and CBCT reconstructed images ($p = 0.013$) (Table 5.7). However, two-group comparisons, with p values adjusted for multiple contrasts, showed few differences, indicating only that maxillary and mandibular posterior teeth both differed significantly from maxillary anterior teeth when diagnostic outcome was assessed by periapical radiographs; and maxillary posterior teeth differed significantly from mandibular anterior teeth when outcome was diagnosed by CBCT ($p < 0.01$).

Outcome	X ray	CBCT
1 - new lesion	1 (0.8)	9 (7.3)
2 - enlarged lesion	1 (0.8)	5 (4.1)
3 - unchanged lesion	4 (3.3)	5 (4.1)
4 - reduced lesion	10 (8.1)	27 (22.0)
5 – resolved lesion	33 (26.8)	35 (28.5)
6 – no lesion before/after treatment	74 (60.2)	42 (34.0)
Total	123 (100)	123 (100)

Outcome of each root was assessed using the following criteria: 1-new periapical lesion, 6-no periapical i.e. before or after treatment. With multi-root teeth, the 'worst' root determined the outcome.

Table 5.6a Frequency distribution (percentage) of outcome of treatment for each tooth assessed using periapical radiographs (X ray) and cone beam computed tomography (CBCT).

	X ray	CBCT
Teeth with new lesions (outcome 1)	1 (1.3)	9 (17.6)
Teeth with no new lesions (outcome 6)	74 (98.7)	42 (82.4)
Total number of teeth showing no pre-operative radiolucency	75	51

Outcome of each root was assessed using the following criteria: 1-new periapical lesion, 6-no periapical i.e. before or after treatment. With multi-root teeth, the 'worst' root determined the outcome.

Table 5.6b. Outcome of treatment for each tooth as a number (percentage) with periapical radiographs (X ray) and cone beam computed tomography (CBCT) of teeth with no pre-operative peri-apical radiolucency, ($p < 0.001$ chi-square test).

	X ray	CBCT
Teeth with reduced lesions (outcome 4 & 5)	43 (89.6)	62 (86.1)
Teeth with enlarged/unchanged lesions (outcome 2 & 3)	5 (10.4)	10 (13.9)
Total number of teeth showing pre-operative radiolucency	48	72

Outcome of each root was assessed using the following criteria: 2-enlarged periapical lesion, 3-unchanged periapical lesion, 4-reduced periapical lesion, 5-resolved periapical lesion.

Table 5.6c. Outcome of treatment for each tooth as a number (percentage) periapical radiographs (X ray) and cone beam computed tomography (CBCT) of teeth with existing peri-apical radiolucency, ($p = 0.759$ chi-square test).

	X ray				CBCT			
	Tooth type				Tooth type			
Outcome Category*	maxillary posterior	mand posterior	maxillary anterior	mand anterior	maxillary posterior	mand posterior	maxillary anterior	mand anterior
1	0 (0.0)	1 (2.1)	0 (0.0)	0 (0.0)	3 (6.5)	6 (12.8)	0 (0.0)	0 (0.0)
2	1 (0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (4.4)	2 (4.3)	0 (0.0)	1 (11.1)
3	0 (0.0)	3 (6.4)	0 (0.0)	1 (11.1)	3 (6.5)	2 (4.3)	0 (0.0)	0 (0.0)
4	3 (6.5)	4 (8.5)	3 (14.3)	0 (0.0)	14 (30.4)	8 (17.0)	5 (23.8)	0 (0.0)
5	10 (21.7)	9 (19.2)	12 (57.1)	2 (22.2)	5 (10.9)	13 (27.7)	10 (47.6)	7 (77.8)
6	32 (69.6)	30 (63.8)	6 (28.6)	6 (66.7)	19 (41.3)	16 (34.0)	6 (28.6)	1 (11.1)
Total	46 (100)	47 (100)	21 (100)	9 (100)	46 (100)	47 (100)	21 (100)	9 (100)

* Outcome was assessed using the following criteria: 1-new lesion, 2-enlarged lesion, 3-unchanged lesion, 4-reduced lesion, 5-resolved lesion, 6-no lesion before or after treatment.

Table 5.7. Frequency distribution (percentage) of outcome of endodontic treatment with periapical digital radiography (X ray) and cone beam computed tomography (CBCT) for maxillary posterior, mandibular (mand) posterior, maxillary anterior and mandibular (mand) anterior teeth.

Comparison between periapical radiographs and reconstructed CBCT images revealed a statistically significant difference in the number of occurrences of each diagnostic outcome for maxillary posterior teeth ($p=0.002$). There was also a difference in outcome for mandibular anterior teeth between the 2 radiographic systems which approached statistical significance ($p=0.039$). There was no difference in outcome for mandibular posterior ($p=0.129$) and maxillary anterior ($p=0.711$) teeth between periapical radiographs and CBCT reconstructed images

5.4 Discussion

In this prospective clinical study the radiographic diagnostic outcome of endodontic treatment was assessed using periapical radiographs and reconstructed CBCT images. To the author's knowledge this is the first published prospective, longitudinal clinical study in humans comparing endodontic treatment outcome using both radiographic techniques before treatment, and at a one year review. A recent retrospective clinical study assessed endodontic

outcome with periapical radiographs and reconstructed CBCT images but no pre-treatment CBCTs were taken (Liang *et al.* 2011).

An important aspect that has to be addressed is the potential presence of false readings in the reconstructed CBCT images, considering that the resolution of CBCT images is lower than that of periapical radiographs. It would have been unethical to undertake a histologic assessment of the patient's periapical tissues, and it was not possible to perform an *in-vivo* animal study as the University did not have special licence for the quarantine of animals for these types of investigations. However, the investigation described in chapter 2 on the diagnostic accuracy of small volume CBCT and periapical radiographs for the detection of artificially created periapical lesions on dry mandibles clearly demonstrated that CBCT was far superior to periapical radiographs in terms of sensitivity (100% vs 25%, respectively), however, both systems gave perfect results (100%) for specificity. Similar findings were reached in an *in-vivo* animal study (Paula-Silva *et al.* 2009c).

The 6 point classification used the present study allowed us to assess the nature of existing periapical lesions with sufficient detail. The one year follow-up of patients in the present study conformed to quality guidelines for endodontic treatment (European Society of Endodontology 2006). As with all the previous investigations in this thesis, each examining session was carried out in a quiet, dimly lit room to optimise the viewing conditions (Welander *et al.* 1983). Ng *et al.* (2011) has suggested that the ideal choice of statistical analysis would be to analyse time to healing (success) with survival analysis techniques, but this would require regular follow-up of all patients. However, the likelihood of high recall rates reduces with increasing length of follow-up after treatment. Interestingly, Ørstavik has reported that peak incidence of healing and emerging apical periodontitis detected on periapical radiographs is 1 year (Ørstavik 1996).

Although a higher patient recall rate at review would have been ideal, however, the 75% recall rate achieved in the present study was acceptable.

The patients who were contacted but declined a review appointment were all asked if their root treated tooth was symptomatic; they all reported no symptoms and confirmed that the tooth was functional. Patients who were not reviewed fell into one of 2 categories. Firstly, those who declined a review appointment as they felt they could not justify and/or afford the time and/or indirect costs of attending. The second group consisted of patients who could not be contacted as they either did not return messages or had moved away without leaving forwarding contact details. The difficulty in recalling patients in clinical studies is well documented (Sprague *et al.* 2003, Ross *et al.* 2009). Reasons often cited for failing or the inability to attend review appointments include: expense (for example, transport), the transient nature of the working population in large cities and lack of time, including travelling to and from work/home (Friedman *et al.* 2003, Sprague *et al.* 2003, Ng *et al.* 2011).

As in chapter 4, when assessing multi-rooted teeth, the periapical status on each identifiable root was noted, thus allowing the outcome of matching pairs of roots using periapical radiographs and CBCT reconstructed images to be assessed.

A single periapical radiograph was assessed for each tooth. This approach is similar to other published work assessing outcome of endodontic treatment (Friedman *et al.* 2003, de Chevigny *et al.* 2008). This was also consistent with the assessment of the periapical status before treatment started (chapter 4). This type of visual comparison has been used in the majority of outcome studies (de Chevigny *et al.* 2010, Ng *et al.* 2011). There is scant evidence to suggest that parallax views are consistently more accurate than a single view for detecting periapical radiolucencies in different regions of the mouth. A study comparing the ability of one periapical radiograph with 2 parallax views did not find any

statistical difference in the detection of simulated periapical lesions (Soğur *et al.* 2012). In addition, patients in the present study were being exposed to a CBCT scan, therefore it would have been difficult to justify a second periapical radiograph on the basis of the increased radiation dose the patient would have been exposed to.

Recently, volumetric assessment of periapical radiolucencies visualized on CBCT images has been carried out (Paula-Silva *et al.* 2009b), however, the accuracy of these *in-vivo* volumetric measurements has not been confirmed. Kayipmaz *et al.* (2012) has used the Cavalieri principle to calculate bony defect volumes *ex-vivo*, and concluded that accurate volumetric measurements could be obtained with this technique.

The consensus panel agreement was acceptable, at least where sufficient roots were presented for diagnosis. The low Kappa value for root 3 was due to the small sample size. However, agreement for the intra-consensus panel assessment that was used in the main study was excellent. The examiners were both experienced in the use of CBCT for managing endodontic problems including detecting radiographic signs of periapical periodontitis. Both radiographic techniques were standardized as were the viewing sessions, therefore minimising the overall observer variation due to faults in radiographic technique, knowledge and judgment (Robinson 1997, Brearley & Westwood 2007). As would be expected, inter-examiner agreement with CBCT was higher than for periapical radiographs, confirming its superior reliability. This is in agreement with the results reported by other studies assessing periapical radiolucencies with CBCT (Sogur *et al.* 2009, Lennon *et al.* 2011, Liang *et al.* 2011). The intra-consensus panel agreement also followed a similar trend of being higher with CBCT (0.858-0.915) compared with periapical radiographs (0.736-0.776). These levels of agreement were excellent (Landis & Koch 1977).

Anatomical noise and the compression of three-dimensional anatomical structures were probably the major contributory factors which resulted in the poorer kappa scores with periapical radiographs. Ideally, having more examiners would have made the present study stronger. However, it would have been very difficult to recruit more examiners who would have been willing to assess over 1000 reconstructed CBCT images and datasets. Previous prospective endodontic outcome studies have also used 1 or 2 examiners (Friedman *et al.* 2003, Ng *et al.* 2011).

Several investigations have shown that inter-examiner agreement can be as little as 25% between examiners (Tewary *et al.* 2011), and one 'outlier examiner' can skew results (Goldman *et al.* 1971, Tewary *et al.* 2011). As with the investigation described in chapter 4, viewing sessions were kept as short as practically possible to reduce the likelihood of examiner fatigue.

The prevalence of unresolved periapical radiolucencies after primary root canal treatment was significantly higher when teeth were assessed with CBCT compared with periapical radiographs regardless of whether the data was assessed by individual roots or by tooth. When individual roots were assessed as 'healed' there was a statistically significant difference in the diagnostic outcome of endodontic treatment (92.7% with periapical radiographs *versus* 73.9% with CBCT). When the outcome was assessed as either 'healed' or 'healing', the prevalence increased to 97.2% and 89.4%

Previous studies, using periapical radiographs alone, have concluded that diagnostic outcome results were similar regardless of whether outcome was assessed as 'tooth' or 'root' units (Hoskinson *et al.* 2002, Ng *et al.* 2011); we also came to a similar conclusion in the present study.

More roots appeared not to have changed from their pre-treatment healthy periapical status (outcome 6) with periapical radiographs (75.2%) compared with CBCT (50.9%), i.e. they retained their healthy pre-treatment periapical status. Fourteen times more new periapical radiolucencies (outcome 1) were detected with CBCT compared with periapical radiographs for outcome 1. This may be partially explained by the fact that new periapical radiolucencies are clearly very small in size and more easily detected by the most sensitive technique (CBCT).

Interestingly, these teeth were all molars, and only 1 was associated with sealer extrusion, this suggests that foreign body reactions were not associated with the failure of teeth that did not show any periapical radiolucency pre-operatively, and that the technical challenges associated with the treatment of molars might have reduced the success rate in these teeth. It is possible that these radiolucencies are transient. The aim is to review all these patients at 2, 3 and 4 years post-treatment which will give us a better understanding of the long-term dynamics of periapical healing. The prevalence of failure of primary root canal treatment in teeth with pre-treatment periapical radiolucencies (outcome 2 & 3) was higher with CBCT (13.9%) compared with periapical radiographs (10.4%). This difference was not statistically significant ($p=0.109$)

The results from the assessment using periapical radiographs in the present study is in agreement with the literature (Friedman *et al.* 2003, de Chevigy *et al.* 2008, Ng *et al.* 2008) that associates the absence of a pre-operative periapical radiolucency with a higher success rate of primary root canal treatment. However, more failures were observed with CBCT as determined by the emergence of new periapical radiolucencies

Teeth with no pre-operative periapical radiolucency can be either: teeth presenting with a carious exposure, irreversible pulpitis and virtually no infection

within the root canal space, or teeth with a root canal infection that is not sufficient to provoke an inflammatory reaction of the periapical tissues (Ricucci & Spångberg 2009). All 9 teeth with failed root canal treatment in outcome 'category 1' had vital pulp tissue. It is unlikely that endodontic treatment was unable to remove the few bacteria that might have been present within the root canal space of these vital and/or necrotic cases. If this was true, the same problem should have occurred in the far more heavily infected root canals that presented with a pre-operative periapical radiolucency, which should result in higher failure rates in teeth with pre-operative radiolucencies. It is possible that bacteria are introduced into the root canal space during the root canal treatment itself despite the use of rubber dam, sterile instruments and the adherence of strict aseptic practices. Niazi *et al.* (2010) demonstrated that nosocomial infections from bacteria such as *P.acnes* and *S.epidermidis* are likely to be associated with failures of root canal treatments.

It is possible that the defence mechanisms in the periapical tissues, already activated by a heavy infection within the root canal space of teeth with radiographic signs of periapical periodontitis are more able to cope with an extra intake of bacteria than vital or lightly infected teeth (outcome 1) that suddenly face a bacterial challenge developing *ex novo*. In fact, the commensal to pathogen switch has been well documented in the literature in relation to bacteria such as *E.faecalis* that are also known endodontic pathogens (Mason *et al.* 2011). Another possible cause of periapical periodontitis includes a long-term transient inflammatory reaction to endodontic treatment resulting in a very slow healing process, and/or apical root fracture due to instrumentation. Our results concur with Paula-Silva *et al.* (2009b) who also detected more failures (new periapical radiolucencies) with CBCT compared with periapical radiograph in vital teeth which had no pre-operative periapical radiolucency.

Paula-Silva *et al.* (2009b) assessed the diagnostic outcome of endodontic treatment in dog's teeth after 6 months. In their study a favourable outcome (i.e. both healed and healing) was reached in 79% and 35% of roots assessed with periapical radiographs and CBCT respectively. Therefore, the prevalence of apical radiolucency was 44% higher with CBCT. In the present investigation there was a 7.8% difference between the 2 radiographic systems when diagnostic outcome was assessed using the same criteria. The shorter review procedure of only 6 months and the complex anatomy of dogs' teeth being potentially more challenging to adequately disinfect may have contributed to the difference in outcome results in the Paula-Silva study. Interestingly, 67% of the roots had pre-existing periapical radiolucency with CBCT in their study, compared to only 44% (outcomes 2-5) in the present investigation.

In a recently published retrospective study, periapical radiolucencies were detected in 12.6% of cases with periapical radiographs and 25.9% of CBCT scans 2 years after endodontic treatment had been completed (Liang *et al.* 2011). However, this study had a poor recall rate (36%), was limited to teeth with no radiographic signs of pre-treatment periapical periodontitis, and did not include maxillary molar teeth. Christiansen *et al.* (2009) detected 28% more periapical radiolucencies associated with roots assessed with CBCT compared with periapical radiographs 1 year post endodontic surgery, they also found that periapical radiographs underestimated the size of a periapical radiolucency compared to CBCT.

The higher prevalence of periapical radiolucencies detected with reconstructed CBCT images in the present study is due to their increased accuracy compared with periapical radiographs, which is well documented (chapter 2, Paula-Silva *et al.* 2009b, 2009c). All these studies compared the radiographic findings of periapical radiographs and reconstructed CBCT images to a reference standard

and all concluded that CBCT had a higher degree of diagnostic accuracy compared with periapical radiographs for detecting periapical radiolucencies. The reason for this improved diagnostic accuracy is principally because CBCT software creates reconstructed images from slices of data in any plane and location of the region of interest, thus eliminating lack of three-dimensional assessment and anatomical noise which hampers the accuracy of periapical radiography. This has been described in depth in chapter 1. This results in a higher signal-to-noise ratio and image contrast, thus improving the detection of periapical radiolucencies (Bender 1997, Sogur *et al.* 2009). In addition, unlike periapical radiographs, the reconstructed CBCT images have been shown to be a very accurate representation of the region of interest (Murmulla *et al.* 2005, Ludlow *et al.* 2007, Mischkowski *et al.* 2007, Stratemann *et al.* 2008).

Well-designed prospective clinical studies are essential to determine the diagnostic outcome of endodontic treatment. The results from these studies allow clinicians to estimate the prognosis of various treatments, thus greatly assisting the patient to make an educated informed decision on the best treatment option for their unique endodontic problem (Friedman *et al.* 2003, Wu *et al.* 2009).

Cone Beam Computed Tomography is more sensitive and accurate at detecting radiographic signs of periapical periodontitis, which may otherwise go undetected when assessed with conventional two dimensional radiographs (Chapter 2, Stavropoulos & Wenzel 2007, Özen *et al.* 2008, Paula-Silva *et al.* 2009a, Soğur *et al.* 2012). Such information may reveal different outcome predictors for endodontic treatment than conventional outcome studies based on assessment of periapical radiographs, and also give more of an insight into the healing dynamics of periapical periodontitis (Wu *et al.* 2011). For example, perhaps CBCT should be considered when comparing different treatment strategies (single versus multiple visit endodontic treatment, or different preparation and/or

instrumentation techniques); the increased accuracy of CBCT may highlight clinically relevant differences that may otherwise not be detected with radiographs (Ng *et al.* 2011). The investigation is ongoing and patients will continue to be recalled on a periodic basis and the data analysed for up to 4 years post-treatment.

5.5 Conclusion

Diagnosis using CBCT indicates a lower healed and healing rate for the outcome of primary endodontic treatment when compared to digital periapical radiographs. Molar teeth with no pre-operative periapical radiolucency revealed a fourteen-fold higher failure rate when assessed using CBCT (17.6%) compared with periapical radiographs (1.3%).

Chapter 6

6. The detection and management of root resorption lesions using intraoral radiography and cone beam computed tomography.

6.1 Introduction

Root resorption is the loss of hard dental tissue (i.e. cementum and dentine) as a result of odontoclastic cell action. Root resorption is inhibited by the protective unmineralized innermost predentine and outermost precementum surfaces of the root (Lindskög *et al.* 1983, Wedenberg & Lindskög 1985, Heithersay 2004). Damage to the odontoblast and predentine layer (Wedenberg & Lindskög 1985) or precementum (Lindskög *et al.* 1983) may result in exposure of the mineralized dentine and cementum, respectively. Osteoclasts rapidly colonize the damaged root surface and will then start resorbing it. Damage to the inner predentine and outer precementum results in internal resorption and external resorption, respectively. The resorptive process may be inconsequential, lasting for 2-3 weeks only (Fuss *et al.* 2003). However, with continual stimulation (for example by infection (Gunraj 1999, Tronstad 2002), or pressure Fuss *et al.* 2003) the osteoclasts will continue to resorb the damaged surface of the root which may result in extensive damage to the tooth.

Resorption defects can be challenging to diagnose correctly which may result in inappropriate treatment being carried out (Chapnick 1989, Gulabivala & Searson 1995, Patel & Pitt Ford 2007, Patel & Dawood 2007). Parallax views may be used in an attempt to improve detection, diagnosis and subsequent management of suspected resorptive lesions (Kleoniki *et al.* 2002, Kamburoğlu *et al.* 2008) An accurate diagnosis is essential for an appropriate treatment plan to be devised (Patel *et al.* 2010).

Internal resorption is usually caused by chronic pulpal inflammation (Masterton 1965, Çalışkan & Türkün 1997, Whitworth 2004) or dental trauma (Wedenberg & Lindskog 1985, Wedenberg & Zetterqvist 1987, Çalışkan & Türkün 1997). Localised pulpal injury results in the demise of the adjacent protective odontoblast layer exposing the mineralised dentine, which then becomes resorbed by osteoclasts (Patel *et al.* 2010). The coronal pulp tissue subsequently becomes necrotic and infected which sustains the resorption lesion (Wedenberg & Lindskog 1985). Apical vital tissue is required for internal resorption to progress. The cause of external cervical resorption is not fully known (Heithersay 2004). Several possible aetiological factors have been suggested for external cervical resorption, most of which result in damage to the cervical region of the root surface these include; dental trauma (Heithersay 1999), orthodontic treatment (Tronstad 2002), intra-coronal bleaching (Harrington and Natkin 1979), periodontal treatment (Trope 2002) and idiopathic aetiology (Gunraj 1999, Liang *et al.* 2003).

Radiographically, internal root resorption appears as a ballooning out of the root canal. The resorption lesion is radiolucent and has smooth, well defined margins and is oval or round in shape (Çalışkan & Türkün 1997, Whitworth 2004). The radiographic appearance of external cervical root resorption depends on the severity of the lesion. Early lesions appear as cloudy radiolucencies in the cervical region of the tooth and the border of the defect is usually poorly defined. The root canal walls should be visible and running vertically through the radiolucent defect, indicating that the lesion lies on the external surface of the root (Heithersay 1999, Tronstad 2002, Heithersay 2004). Root resorption may be confirmed using the parallax radiograph technique (Haapasalo & Endal 2006, Patel & Dawood 2007). The parallax technique may be helpful to detect and determine the location (palatal or labial) of the external cervical root resorption lesions. However, periapical radiographs do not provide an indication of the true

dimensions of such lesions (Kim *et al.* 2003, Patel *et al.* 2009b). The resorption defect may spread within the root in all directions, this may not be reflected in the size and position of the radiolucency detected on the radiograph (Patel & Dawood 2007).

Internal resorption and external cervical resorption may be difficult to distinguish from one another (Haapasalo & Endal 2006). The parallax radiograph technique may be used to confirm whether the resorption lesion is located the outer or inner aspect of the canal (Haapasalo & Endal 2006, Patel & Dawood 2007). External cervical resorption defects will move in the same (palatal/lingual positioned lesion) or opposite (labial positioned lesion) direction of the first radiograph. However, internal resorption defects will stay in the same position.

One of the major problems with diagnosing and predictably managing internal and external cervical root resorption is that periapical radiographs only reveal limited diagnostic information (Cohenca *et al.* 2007). This has been discussed in chapter 1.

Internal resorption will continue while the pulp has a blood supply, ultimately the pulp becomes necrotic, and with time infected which may result in periradicular periodontitis. In cases where resorption is not too extensive, endodontic treatment may be carried out to retain the tooth. In certain cases internal resorption may be more extensive resulting in perforation of the root wall. In these cases a combined non-surgical/surgical approach or extraction may be necessary. Unlike Internal resorption the pulpal contents plays no role in sustaining external cervical resorption. Treatment depends on the size and accessibility of the lesion. Treatment usually involves raising a full muco-periosteal flap to allow complete excavation of the granulomatous tissue, including any new bone that may have 'replaced' existing granulomatous tissue.

The resorption cavity may then be restored with a direct plastic restoration. In advanced cases, the external cervical resorption lesion may be very close to or have perforated the root canal. Endodontic treatment will need to be carried out in addition to restoring the resorption cavity. It should be borne in mind that the resorption defect is usually larger than it appears radiologically (Patel & Pitt Ford 2007). Extraction may be the only viable option in advanced cases of internal resorption and external cervical resorption. In general, with either type of root resorption the earlier it is diagnosed and treated, the better the prognosis (Patel *et al.* 2009, Kamburoğlu *et al.* 2011).

CBCT has been successfully used to evaluate the true nature and severity of resorption lesions in case reports (Cohenca *et al.* 2007, Patel & Dawood 2007) indicating that the clinician could confidently diagnose and manage the defect.

To date there are no studies which have tested the ability of CBCT to improve the diagnosis of internal and external cervical root resorption. The aim of the present study was firstly to compare the diagnostic accuracy of periapical radiography with CBCT for the detection of internal and external cervical resorption, and secondly to compare the treatment strategies chosen for the management of resorption lesions using periapical radiography and CBCT.

6.1 Materials and Methods

6.1.1 Data collection

The radiographs and CBCT data records of 15 teeth (from 15 patients) were included in this study. The teeth had either been successfully managed by one operator (SP) in specialist practice (n=12), or by endodontic postgraduate students (n=3) under the supervision of the same individual. There was no age limit for inclusion into the study. Approval was sought and granted by Guy's

Research Ethics Committee, REC reference 10/H0804/11 (National Research Ethics Service, England), refer to appendix IV.

The study population consisted of 10 males and 5 females.

- 5 teeth were diagnosed with internal resorption
- 5 teeth were diagnosed with external cervical resorption
- 5 teeth were controls (i.e. no resorption present).

The periapical radiographs and CBCT data were assessed by a consensus committee consisting of 3 experienced specialist endodontists who confirmed the diagnosis and ideal treatment plan for each case. The 3 members of this consensus committee between them had 60 years experience in clinical and academic Endodontology. All 3 members of the consensus committee independently assessed the resorption cases. There was unanimous agreement between the consensus committee. Their diagnoses were confirmed in all cases when the resorption lesions were treated, in all cases the diagnoses of the consensus committee were correct.

6.1.2 Radiographic technique

Patients were radiographed with a dental X-ray machine (Planmeca Prostyle) using a digital CCD sensor (Schick Technologies) with exposure parameters described in chapter 4 using a paralleling technique. CBCT scans were either taken using a small volume CBCT scanner (3D Accuitomo 80, J Morita) with same exposure parameters as described in chapter 4, or a large volume scanner (i-CAT, Imaging Sciences International, Hatfield, PA, USA) with, exposure parameters of 120 Kv, 5 mA and 20s).

CBCT data were reformatted to align the root axis with the vertical plane in the sagittal and coronal views. The brightness and contrast of all the acquired images was enhanced to improve visualisation of the resorption lesions. All CBCT data were reformatted (0.125 mm slice intervals and 1.5 mm slice thicknesses).

6.1.3 Radiological assessment

Six examiners (two specialist endodontists and four endodontic postgraduates) individually assessed the radiographs and CBCT scans in the following sequence: session 1 - radiographs, session 2 - CBCT scans, session 3 - radiographs and CBCT scans repeated (to assess intra-observer agreement).

Prior to assessing the experimental material all the examiners were reminded of the salient features of resorption lesions using sample radiographs and CBCT images from 5 cases with root resorption, which were not used in this study. The examiners were then trained using radiographs and CBCT images of teeth (n=6) with and without internal and external cervical root resorption. Only examiners who were able to correctly diagnose images in at least 80% of the cases were allowed to go on to assess the test cases. After the completion of this training session the examiners were shown the 'training' cases again with a member of the consensus committee who discussed the salient diagnostic features in each case. This served to consolidate the knowledge of the radiographic features of internal and external cervical resorption lesions. These discussion sessions with the consensus committee member were carried out over 3 sessions, with 2 examiners in each session.

The test images were randomly ordered in each session and viewed as a PowerPoint presentation® (Microsoft) on the same laptop computer (Toshiba Portege) used in chapter 2. A CBCT image that best confirmed the presence or absence of the resorption defect in the sagittal and coronal planes was used as

the starting point for each tooth observation. Examiners also had access to the raw CBCT data allowing them to scroll through any of the orthogonal scans. All images were assessed in a dark room.

Examiners were asked to note down the presence or absence of internal resorption and/or external cervical root resorption and their treatment plan (Table 6.1a-b & Figures 6.1-3). In each case there was only one correct diagnosis and treatment option. The diagnosis and preferable treatment plan had been previously established by the consensus committee, and in resorption cases the diagnosis and treatment plan was confirmed during the treatment of the lesion.

There was at least a one week interval between each session. Eight radiographs and 8 CBCT scans were randomly chosen and assessed in session 3 to assess intra-examiner agreement.

	Definitely present	Probably present	Unsure	Probably not present	Definitely not present
Internal resorption					
External cervical resorption					

Table 6.1.a Diagnosis questionnaire which examiners completed for each case.

	Very sure	Reasonably sure	Unsure	Reasonably unsure	Very unsure
Leave alone					
Review					
Non-surgical endodontic treatment					
Surgical endodontic treatment					
Combination of non-surgical & surgical endodontic treatment					
Extraction					

Table 6.1.b Treatment planning questionnaire which examiners completed for each case.

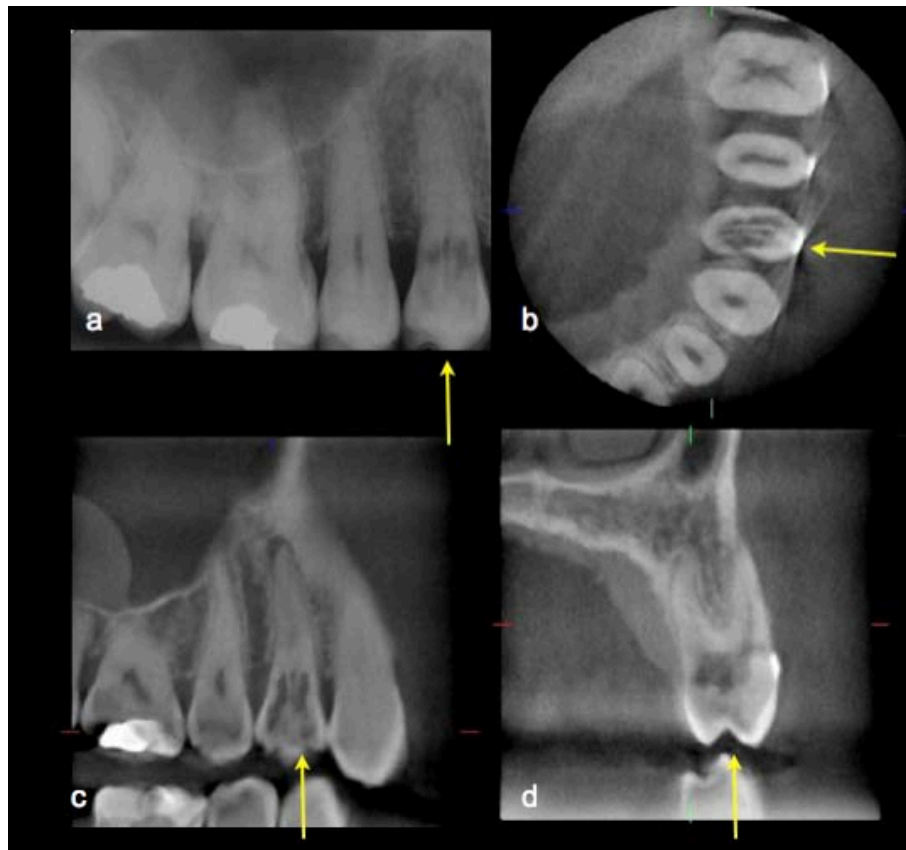


Figure 6.1. (a) Radiograph shown in session 1 and 3 to assess diagnostic accuracy of periapical radiographs. There are radiolucent areas (yellow arrows) around the cervical third of the root canal. (b-d) Reconstructed CBCT images (axial, coronal and sagittal) views of the same tooth shown in session 2 and 3 to assess diagnostic accuracy of cone beam computed tomography. An external cervical resorptive lesion can clearly be detected surrounding the root canal.

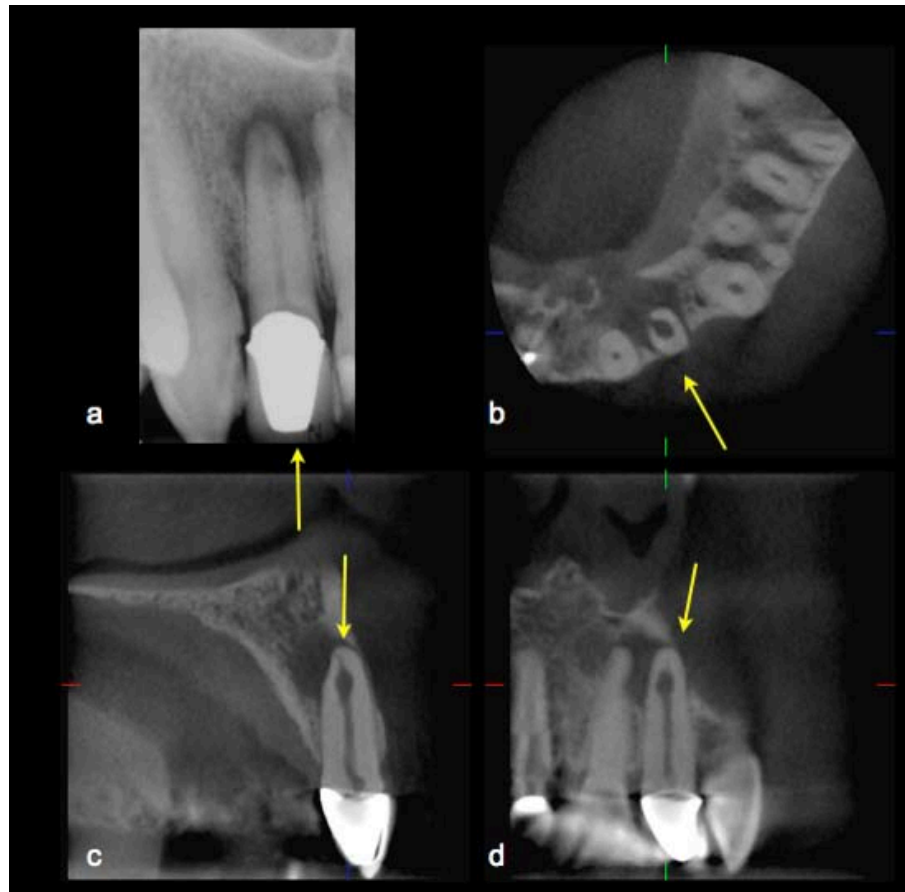


Figure 6.2 (a) Radiograph shown in session 1 and 3 to assess diagnostic accuracy of periapical radiographs. The apical third of the canal balloons out, and is a uniform radiolucency (yellow arrow). (b-d) Reconstructed CBCT images (axial, coronal and sagittal) views of the same tooth shown in session 2 and 3 to assess diagnostic accuracy of cone beam computed tomography. An internal inflammatory resorptive lesion which has perforated through the palatal root can clearly be seen.

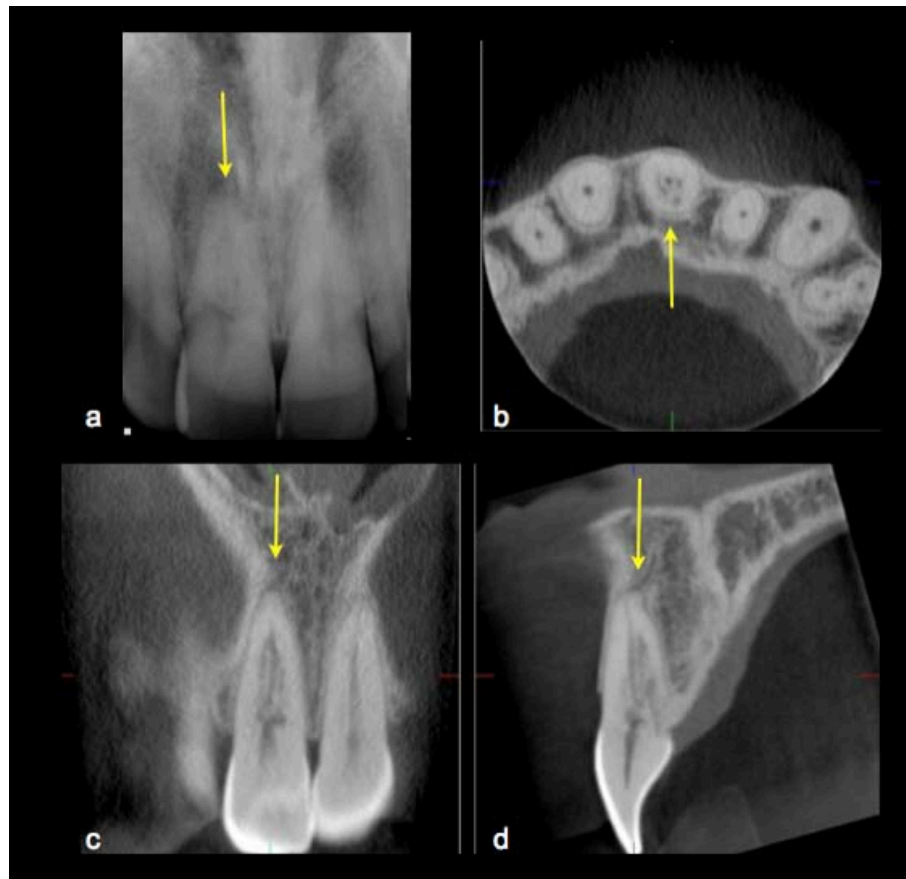


Figure 6.3 (a) Radiograph shown in session 1 and 3 to assess diagnostic accuracy of periapical radiographs. A cloudy radiolucency (yellow arrow) is present in the mid-third of the root. (b-d) Reconstructed CBCT images (axial, coronal and sagittal) views of the same tooth shown in session 2 and 3 to assess diagnostic accuracy of cone beam computed tomography. An external cervical root resorption lesion can clearly be seen, note the severity of the lesion.

6.1.4 Data analysis

Stata™ software (Stata 9) was used to analyse the raw data. Sensitivity, specificity and predictive values were determined; ROC curve analysis was used to assess the diagnostic accuracy of each examiner and each imaging system in detecting the presence of each type of resorption defect against the alternate type of defect and controls. Summary data were described using mean (standard deviation) and median (inter-quartile range) to accommodate the small sample size, and differences between radiographs and CBCT were analysed using Wilcoxon matched-pairs, signed ranks test. Inter-examiner and intra-examiner agreement was assessed by Kappa statistics for scores from both the periapical radiographs and CBCT scans.

6.2 Results

6.2.1 Diagnosis

The overall sensitivity of periapical radiography was lower than CBCT (Table 6.2). The ROC analysis revealed that periapical radiography had a lower median AUC value (0.780) than CBCT (1.000) for diagnosing internal resorption ($p=0.027$). Similarly, the mean AUC value (0.830) of periapical radiography was lower than CBCT (1.000) for diagnosing external cervical resorption ($p=0.027$) (Table 6.3-6.4).

The kappa value for inter-examiner agreement was 0.365 and 0.925 for periapical radiography and CBCT, respectively for the diagnosis of internal resorption. The kappa value for inter-examiner agreement was 0.444 and 0.951 for periapical radiography and CBCT, respectively for the diagnosis of external cervical resorption.

Intra-examiner agreement was assessed in 53% (8 of the 15) of the cases for each imaging system in session 3. The median intra-examiner agreement was 0.810 and 0.885 for periapical radiography and CBCT respectively for the diagnosis of internal resorption. The mean intra-examiner agreement was 0.657 and 1.000 for periapical radiographs and CBCT respectively for the diagnosis of external cervical resorption (Table 6.5).

	Sensitivity	Specificity	PPV	NPV
Radiographs (5)	0.590 (0.216) 0.51 [0.46-0.86]	0.974 (0.064) 1.00 [1.00-1.00]	0.945 (0.136) 1.00 [1.00-1.00]	0.713 (0.120) 0.70 [0.61-0.83]
Radiographs (4+5)	0.741 (0.220) 0.86 [0.46-0.89]	0.957 (0.069) 1.00 [0.90-1.00]	0.944 (0.086) 1.00 [0.83-1.00]	0.788 (0.148) 0.83 [0.61-0.90]
CBCT (5)	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]
CBCT (4+5)	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]

Table 6.2a: Mean (standard deviation), median [inter-quartile range] of Sensitivity, Specificity, Positive Predictive Value (PPV) and Negative Predictive Value (NPV) for radiographs and CBCT for detecting internal resorption at confidence levels (5) and (4+5).

	Sensitivity	Specificity	PPV	NPV
Radiographs (5)	0.724 (0.302) 0.82 [0.36-1.00]	0.790 (0.076) 0.79 [0.78-0.81]	0.645 (0.114) 0.64 [0.57-0.67]	0.865 (0.157) 0.93 [0.67-1.00]
Radiographs (4+5)	0.941 (0.092) 1.00 [0.85-1.00]	0.845 (0.089) 0.81 [0.78-0.90]	0.723 (0.082) 0.73 [0.71-0.79]	0.976 (0.037) 1.00 [0.93-1.00]
CBCT (5)	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]
CBCT (4+5)	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]	1.000 (0.000) 1.00 [1.00-1.00]

Table 6.2b: Mean (standard deviation), median [inter-quartile range] of Sensitivity, Specificity, Positive Predictive Value (PPV) and Negative Predictive Value (NPV) for radiographs and CBCT for detecting external cervical resorption at confidence levels (5) and (4+5).

Examiner	Radiograph	Cone beam	P value
1	0.800	1.000	0.103
2	0.840	1.000	0.249
3	0.800	1.000	0.103
4	0.720	1.000	0.053
5	0.760	1.000	0.073
6	0.760	1.000	0.073
Mean (SD)	0.780 (0.078)	1.000 (0.000)	
Median [IQR]	0.780 [0.760-0.800]	1.000 [1.000-1.000]	0.027*

* Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity

Table 6.3: Mean (standard deviation), median [inter-quartile range] of area under the curve from ROC analysis of radiographs and CBCT for individual examiners: Correct diagnosis of internal resorption at confidence level (5).

Examiner	Radiograph	Cone beam	p value
1	0.900	1.000	0.134
2	0.880	1.000	0.179
3	0.900	1.000	0.134
4	0.740	1.000	0.051
5	0.760	1.000	0.023
6	0.820	1.000	0.062
Mean (SD)	0.830 (0.070)	1.000 (0.000)	
Median [IQR]	0.850 [0.760-0.900]	1.000 [1.000-1.000]	0.027*

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity

Table 6.4: Mean (standard deviation), median [inter-quartile range] of area under the curve from ROC analysis of radiographs and CBCT for individual examiners: Correct diagnosis of external cervical resorption at confidence level (5).

	Internal resorption		External resorption	
	Radiograph	Cone beam	Radiograph	Cone beam
Inter-examiner	0.365	0.925	0.444	0.951
Intra-examiner	0.711 (0.378) 0.810 [0.600-1.000]	0.788 (0.257) 0.885 [0.529-1.000]	0.625 (0.288) 0.657 [0.556-0.750]	0.966 (0.084) 1.000 [1.000-1.000]

Table 6.5: Kappa values for inter-examiner agreement and mean (standard deviation), median [interquartile range] of Kappa values for intra-examiner agreement in reading radiograph and CBCT for internal and external resorption.

6.2.2 Treatment options

The median percentage correct treatment option selected by the six examiners was 53% and 73% for periapical radiography and CBCT, respectively when assessed using the confidence level of 5 alone (Table 6.6). These results increased to a median of 60% and 80% for periapical radiographs and CBCT respectively when assessed accepting a combination of confidence levels 4 and 5. This difference was statistically significant ($p=0.028$).

There was poor agreement between radiography and cone beam decisions (median kappa = 0.127). The median kappa for intra-examiner agreement was 0.629 and 0.686 for periapical radiographs and CBCT respectively (Table 6.7).

	Confidence level (5)		Confidence level (4+5)	
	Radiographs	CBCT	Radiographs	CBCT
Mean (SD)	52 (15)	74 (9)	60 (10)	79 (8)
Median [IQR]	53 [47-67]	73 [73-80]	60 [53-67]	80 [73-87]

Table 6.6. Mean (standard deviation), median [interquartile range] of percentage correct treatment decisions chosen by the examiners with radiographs and CBCT at confidence levels (5) and (4+5).

	Radiograph	CBCT
Mean (SD)	0.606 (0.274)	0.632 (0.360)
Median [IQR]	0.629 [0.400-0.750]	0.686 [0.250-1.000]

Table 6.7. Mean (standard deviation), median [inter-quartile range] of Kappa values for agreement in treatment decisions between sessions for radiographs and CBCT.

6.3 Discussion

Ideally a diagnostic test for root resorption should be able to correctly detect the presence or absence of different types of root resorption (validity), and should be repeatable, i.e., to generate the same result (reliability). In this study periapical radiographs and reconstructed CBCT images were assessed for their diagnostic accuracy, and their ability to allow the examiner to arrive at the correct treatment option. This is the first clinical investigation that has attempted to validate CBCT for the clinical management of internal and external cervical root resorption.

The test sample size included 10 teeth with either internal or external cervical root resorption defects. This small sample size reflects the rare occurrence of these type of defects (Haapasalo & Endal 2006), and was reached after collecting cases in a specialist practice and in a teaching hospital for almost 2 years. Five additional healthy teeth were included as controls. The results of this study suggest that CBCT imaging of teeth with internal and external cervical root resorption is of value. Although periapical radiography was quite accurate in correctly diagnosing internal and external cervical root resorption, CBCT scans resulted in perfect diagnosis of the presence and type of root resorption. This is also reflected in the sensitivity and specificity results. Periapical radiography was slightly more accurate in diagnosing external cervical root resorption than internal root resorption. The more accurate diagnosis of external cervical root resorption with periapical radiographs may be due to the fact that their irregular margins may be pathognomic of this type of resorption lesion. The examiner's ability to choose the correct treatment option was also improved when CBCT was used. Despite perfect diagnostic accuracy, the treatment decisions with CBCT were only 80% correct when compared with the consensus committee.

Metz (1989) has suggested that a ROC Az value between 0.75-0.80 is acceptable for clinical imaging techniques. The overall diagnostic accuracy of periapical radiographs for detecting internal (ROC Az value 0.780) and external cervical resorption (ROC Az value 0.830) confirmed that periapical radiography is a fairly accurate diagnostic tool. Kamburoğlu *et al.* (2011) also found that the diagnostic accuracy of periapical radiographs was slightly lower for diagnosing internal resorption compared to diagnosing external cervical resorption. Another factor that could account for the poorer accuracy is more anatomical noise masking internal resorption lesions.

The results with periapical radiographs from the present investigation were in the same order of magnitude as previous studies assessing artificially prepared root resorption lesions assessed using ROC analysis (Borg *et al.* 1998, Holmes *et al.* 2001). The perfect diagnostic accuracy of CBCT in diagnosing resorption lesions is a result of the 3-dimensional assessment of these resorption lesions. The CBCT software allows the clinician to select the most favourable orthogonal views for each specific problem being assessed. In addition the thickness of each slice (i.e. how much information) and the interval between each slice may be adjusted. These factors ultimately result in root resorption lesions being significantly more perceptible to the clinician compared with periapical radiographs. Unlike other studies (Borg *et al.* 1998, Kamburoğlu *et al.* 2008a, b) assessing root resorption, a third session was included in our study to assess intra-examiner agreement. As with chapter 2, there was at least a one week interval between each viewing session to reduce the likelihood of the examiner recalling any of the previous cases they had assessed. Images were viewed as a PowerPoint® presentation in order to facilitate the examiners' work.

As this was an *in-vivo* study, the quality of the reconstructed CBCT images produced may have been possibly been less than ideal, for example, beam

hardening and patient movement may have potentially reduced the diagnostic yield of the reconstructed images produced (Scarfe & Farman 2008), yet the diagnostic accuracy of CBCT was perfect.

To improve the diagnostic accuracy of radiographs subtraction imaging has been evaluated *ex-vivo* (Hintze *et al.* 1991, Holmes *et al.* 2001). However, the main limitation of this technique is that it requires near perfect irradiation geometry between serial radiographs; this may not be consistently possible in a clinical setting (Gröndahl & Huuonen, Patel *et al.* 2009).

The examiner's results were compared to the 'reference standard' results of the consensus committee. The question arises as to how valid were the diagnosis and treatment plan for each resorption lesion assessed by the consensus committee. Ideally the 'reference standard' test would be to extract all these teeth to confirm whether the results from assessing the radiographs and CBCT scans correlate to macroscopic and histological findings of the extracted teeth. Obviously, this is not possible in healthy teeth and/or teeth which can be treated successfully. However, in the treatment phase the accuracy of the diagnosis agreed by the consensus panel was confirmed in all cases. Of the 10 resorption cases, 6 were deemed to be successful at 1 year follow up which would suggest that the consensus panel were correct with their treatment options. Two of the remaining 4 teeth that were unsalvageable were extracted. The last two patients did not attend the 1 year recall visit.

The results of this study validate the use of CBCT to determine the presence and type of root resorption. CBCT also appears to be extremely useful for assessing the severity of resorption lesions, which in turn influences the treatment decision made (Cohenca *et al.* 2007). Kamburoğlu *et al.* (2010) compared 2 CBCT scanners (Iluma® and Accuitomo®) at different voxel settings to diagnose the

presence of 0.5mm artificially created internal root resorption defects. They concluded that Accuitomo® CBCT scanner with 0.125mm³ and 0.160mm³ resolution and the ultra (0.1mm³) and high (0.2mm³) resolution Iluma®'s accuracy was in the same order of magnitude. However, the low resolution Iluma® (0.3mm³) setting resulted in poorer results. Another *ex-vivo* study by the same group compared the diagnostic accuracy of CBCT (Iluma®) and periapical radiographs for assessing external cervical and internal inflammatory root resorption defects in mandibular incisors (Kamburoğlu *et al.* 2011). In keeping with the present investigation, they too found that CBCT was more accurate at diagnosing internal and external cervical resorption compared with periapical radiographs. This was despite the fact the examiners were viewing 3 parallax periapical radiograph views. The diagnostic accuracy of CBCT in both the Kamburoğlu studies was lower than the present study despite being set in 'ideal' conditions. One explanation for this is that the *ex-vivo* resorptive defects in the Kamburoğlu studies were much smaller than the *in-vivo* resorptive defects assessed in this study. Despite the fact the resorptive lesions were significantly larger in the present study the diagnostic accuracy of periapical radiographs was similar to the Kamburoğlu studies which assessed far smaller sized resorptive lesions (0.5mm diameter). This was probably due to the fact that despite diagnosing resorption regardless of the size, it is difficult to confirm the true location (internal or external) of resorption lesions with periapical radiographs.

The results from the present study do not necessarily mean that *all* CBCT scanners are suitable for diagnosing the presence and nature of root resorption. Further investigations are required to assess the accuracy of different CBCT scanners, and also the effects of changing the exposure parameters (including voxel size) away from the manufacturers protocols to confirm whether the diagnostic yield is still useful with a lower effective dose (Durack *et al.* 2011). Liedke *et al.* (2009) found that sensitivity and specificity of the iCAT® scanner was

in the same order of magnitude with 3 different voxels settings (0.2, 0.3mm & 0.3mm). Recently, the SEDENTEXCT guidelines have stated that CBCT should be considered for management of resorptive lesions SEDENTEXCT (2011).

Each case in this study was unique, therefore the severity and location of the resorption lesions varied from case to case. In addition anatomical noise and geometrical positioning of the film holder may also have contributed to the poorer diagnostic accuracy of periapical radiography. However, it was important to carry out a clinical study as mechanically 'machined' resorption lesions used in *ex-vivo* studies (Liedke *et al.* 2009, Kamburoğlu *et al.* 2010), although standardised, do not truly reflect the true nature of resorption lesions, as *in-vivo* resorption lesions are not perfect semi-spherical shaped cavities.

It was interesting to note that the favourable results achieved with CBCT in this study were despite the fact that none of the examiners had previous experience in the interpretation of CBCT data. In addition there was no difference in the results between the examiners with different levels of experience (i.e. specialist endodontists versus postgraduate students). The poorer results achieved with periapical radiographs confirmed the difficulty using these 2-dimensional images for correctly diagnosing root resorption.

There may be situations where the quality of the reconstructed CBCT images produced may possibly be less than ideal, for example, beam hardening and patient movement may reduce the diagnostic yield of the reconstructed images produced (Scarfe & Farman 2008). Small FOV CBCT scans should be taken whenever possible, these scan sizes result in a lower radiation dose (Hirsch *et al.* 2008, Loubele *et al.* 2009). The 2 iCAT® scans used in this study were taken prior to the introduction of the Accuitomo scanner into the U.K. dental market (and its subsequent acquisition).

Several studies have concluded that periapical radiographic films and CCD digital sensors perform equally well in diagnosing resorptive lesions (Borg *et al.* 1998, Kamburoğlu *et al.* 2008a, b). In the present investigation the examiners were allowed to adjust the contrast and brightness of the radiographic images. However, they did not have access to any other image enhancement software (for example, colourizing, revealing and inverting) as this type of image manipulation had been shown not be useful in other aspects of endodontic diagnosis (Kamburoğlu *et al.* 2008b). In the present study a LCD screen with a high pixel resolution was chosen to provide an high image quality of the radiographs and CBCT scans. There is evidence to suggest that LCD and high resolution cathode ray tubes are equally effective for assessing CBCT and digital radiographs (Baksi *et al.* 2009). A consensus agreement between all the examiners may also have improved the results from the radiographs used in the study (Molven *et al.* 2002). This was not done in the present study as it does not represent the normal clinical situation for most practitioners.

Only potential examiners who were shown to be competent in a pilot study were accepted as examiners. Intra-examiner agreement was assessed by having a third examiner session, with a selection of randomly selected periapical radiographs and CBCT scans, rather than 2 individual sessions to assess periapical radiographs and CBCT scans respectively. The rationale for this was that the majority of examiners were happier to commit to 3 rather than 4 sessions. The number of cases selected for the third session was kept to 16 to prevent examiner fatigue.

The inter-examiner and intra-examiner agreement was higher with CBCT. This is a result of the examiner being able to select with reconstructed CBCT images with no overlying anatomical noise and having the ability to assess the resorption

lesion in any dimension (for example, reconstructed axial slices). This suggests that even with the parallax technique periapical radiography is an unreliable method of detecting internal and external cervical resorption. This is mainly because of anatomical noise and the compression of three dimensional anatomical structures associated with the periapical radiographs. Similar results were reported by Kamburoğlu *et al.* (2010) for Accuitomo CBCT images. Zachariasen *et al.* (1984) also found a poor inter-examiner agreement with periapical radiographs.

The most conservative figures for the effective dose associated with a periapical radiograph of a tooth is $5\mu\text{Sv}$ (Ngan *et al.* 2003). Therefore 3 parallax views (mesial, distal and no angulation) of an anterior tooth would result in a $15\mu\text{Sv}$ exposure to the patient. The effective dose of a small volume CBCT scan of the anterior maxilla is $29\mu\text{Sv}$ (Loubele *et al.* 2008). This figure is specific to the Accuitomo 3D® CBCT device (J. Morita), which is the same scanner the one used in this investigation to assess 13 of the 15 teeth. Therefore, if the 2 parallax views were substituted for a CBCT scan, the total effective dosage to the patient would be $34\mu\text{Sv}$ (1 periapical radiograph [$5\mu\text{Sv}$] and a 4cm FOV CBCT [$29\mu\text{Sv}$] scan) a $19\mu\text{Sv}$ higher effective dose compared with 3 parallax radiographs ($15\mu\text{Sv}$). This is based on a 360° complete rotation of the CBCT X ray source. Durack *et al.* (2011) has shown that CBCT is an equally reliable method of assessing early external inflammatory lesions with both a 180° and 360° X-ray source rotation. Although Durack's study assessed external inflammatory resorptive lesions, and the present study assessed internal and external cervical resorptive lesions, the gross nature of the disease is similar, i.e. hard tissue defects in the root caused by osteoclastic action. Therefore, one could apply Durack's results to assessing internal and external cervical resorptive lesions; if a 180° ($14.5\mu\text{Sv}$, [half of $29\mu\text{Sv}$]) CBCT scan was carried out, then the total effective dosage would be $19.5\mu\text{Sv}$ (1 periapical radiograph and a 180° rotation CBCT scan). If the

mandibular incisor teeth were being assessed using a 180° scan and a single periapical radiograph the total effective dose would be 11.5 μ Sv (50% of 13 μ Sv + 5 μ Sv); this is less than 3 periapical parallax radiographs (Loubele *et al.* 2009).

Trauma is a documented aetiological cause of internal and external cervical resorptive lesions (Trope 2002, Pohl *et al.* 2005), and it is not uncommon for adjacent teeth to also be injured to varying extents. Therefore, a further benefit of small FOV CBCT scans is that the neighbouring 3-4 teeth may also be assessed for signs of root resorption. Therefore, when the assessing several injured teeth, a small volume CBCT combined with a periapical radiograph may have a lower effective dose than a series of parallax periapical radiographs of each tooth.

6.4 Conclusion

The results of this study indicate CBCT's validity and reliability for detecting the presence of internal inflammatory and external cervical root resorption lesions. Although periapical radiographs resulted in an above average level of accuracy, the superior accuracy of CBCT may result in a review of the radiographic techniques used for assessing the presence or type of resorption lesions. CBCT's superior diagnostic accuracy also resulted in an increased likelihood of correct management of resorption lesions compared with periapical radiographs.

Future research

- Epidemiological studies determining the prevalence of periapical disease in the (root treated) teeth in different population groups.
- Assessment of the impact of systemic diseases (for example, diabetes, cardiovascular disease, HIV) on the periapical status of teeth, and vice versa.
- Well-designed prospective clinical studies to determine the outcome of various types of endodontic treatment with CBCT. These studies would also be able to determine the potential pre-, intra- and post-operative predictors which may influence the outcome of endodontic treatment. These types of studies may reveal not only the true status of the periapical tissues before commencing root canal treatment, but may also potentially influence the way endodontic treatment is carried out.
- Analysis of periapical status using CBCT in patients being managed for atypical facial pain.
- Assessment of the CBCT diagnostic yield with varying exposure parameters, thus determining if the same diagnostic yield is possible with a lower effective patient dose.
- Investigate the feasibility of producing a more radiolucent root filling material, thus minimizing the streaking artifacts produced with CBCT-see appendix II.
- Attempt to classify external cervical and internal root resorption three dimensionally, and produce an index of size and treatability.

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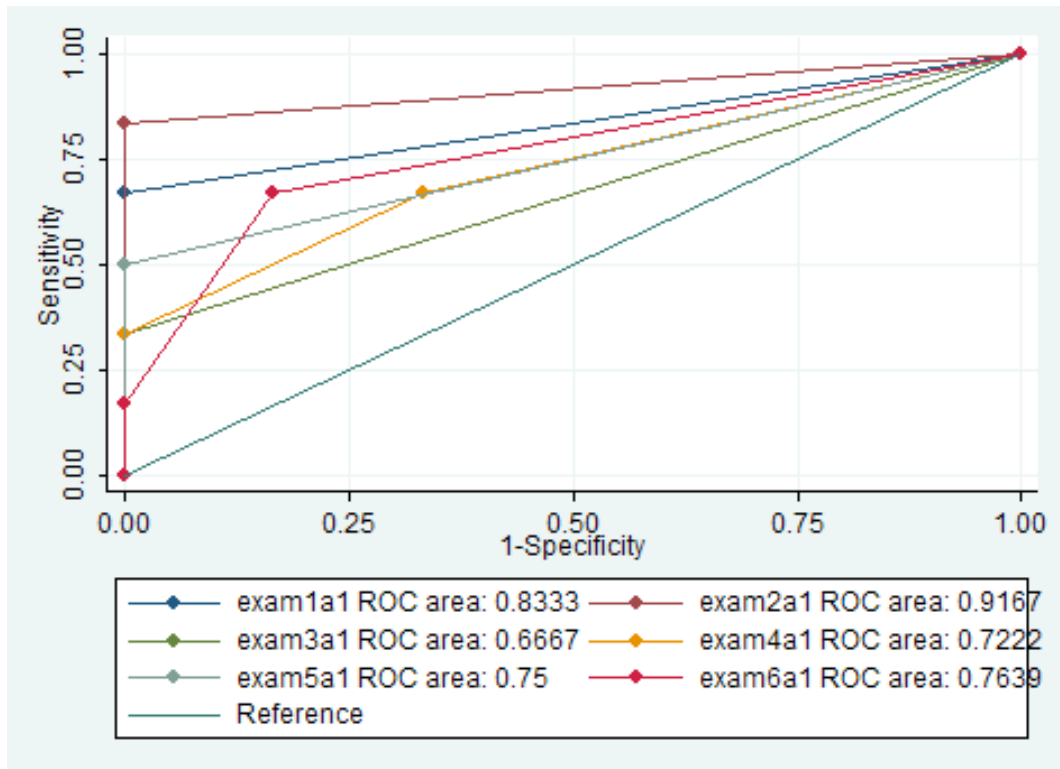
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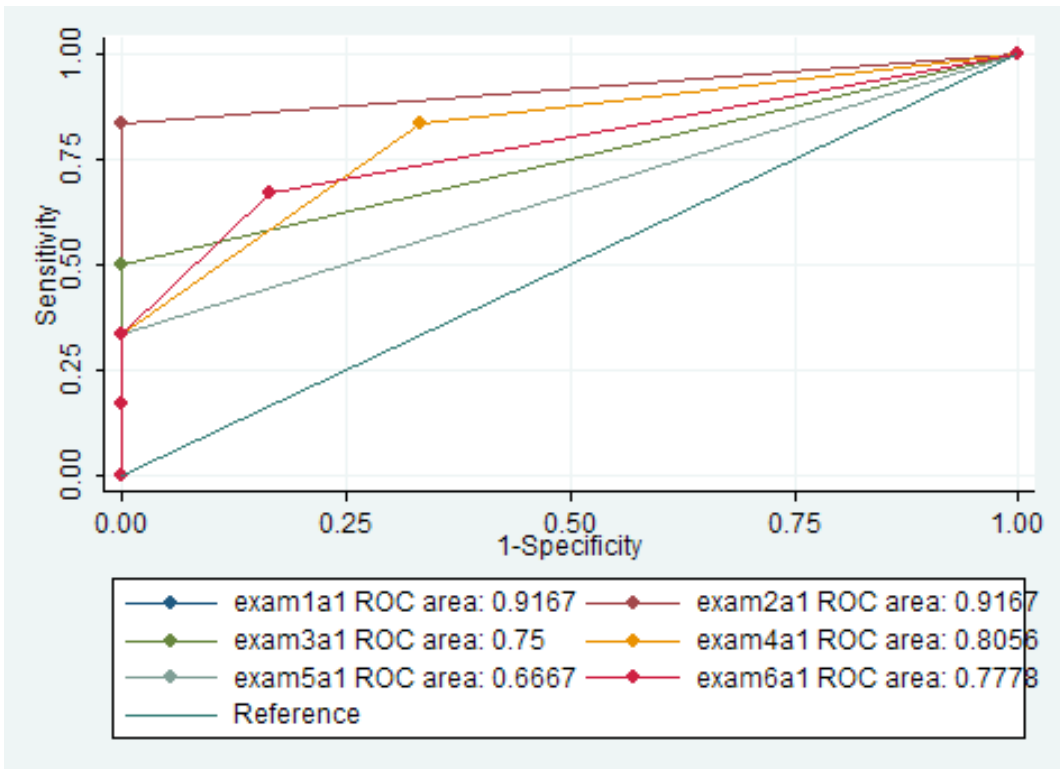
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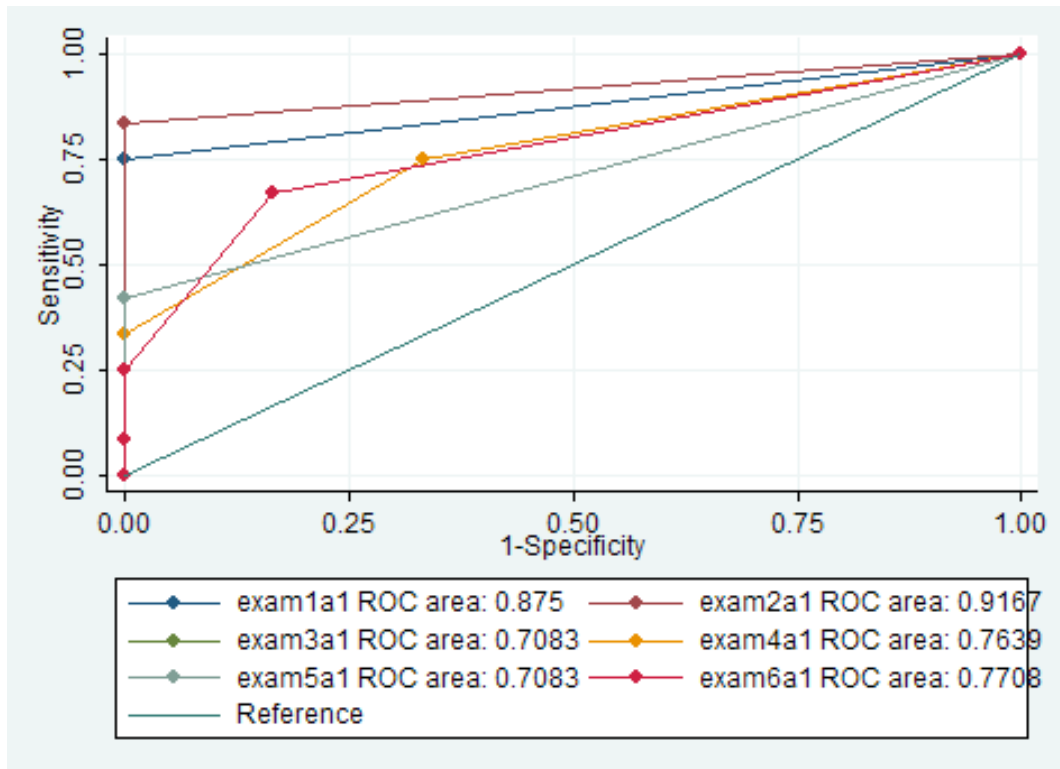
Appendix I



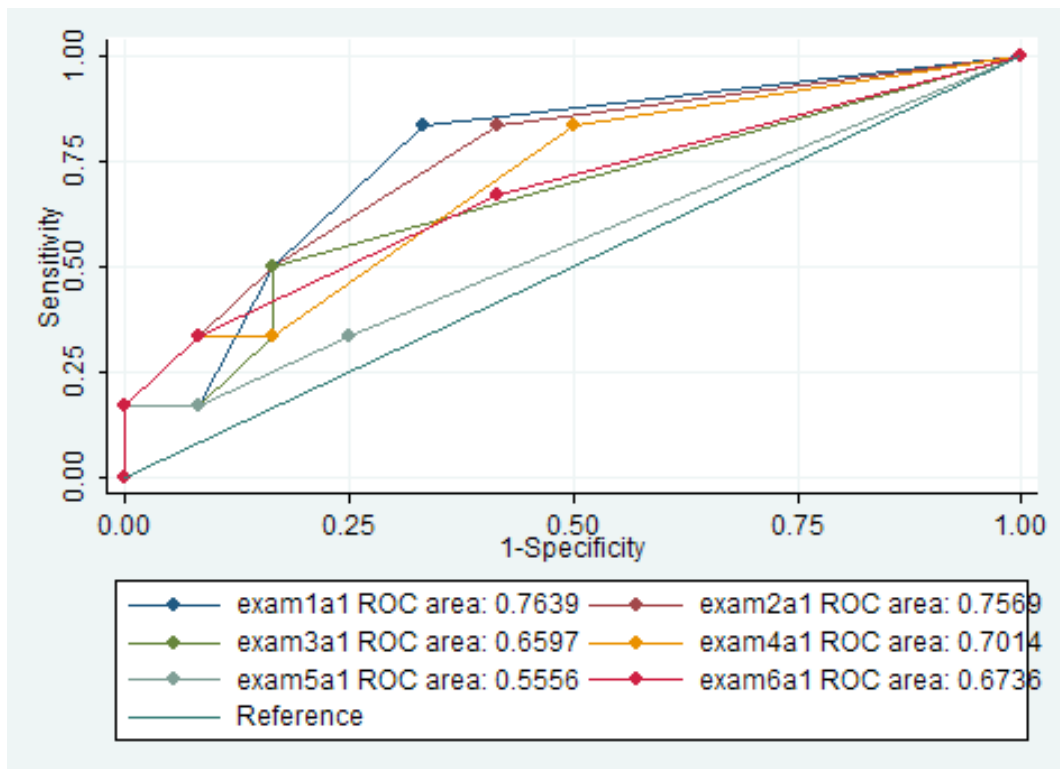
Receiver Operating Characteristic curves for no periapical lesions versus small (2mm) periapical lesions with periapical radiographs.



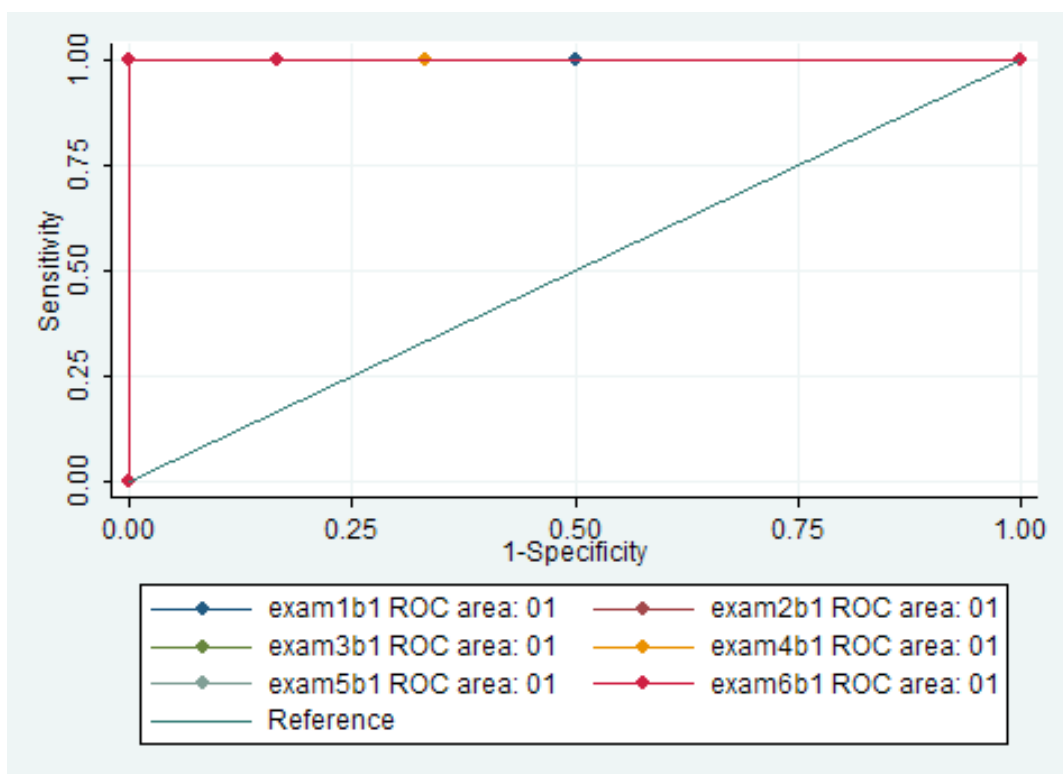
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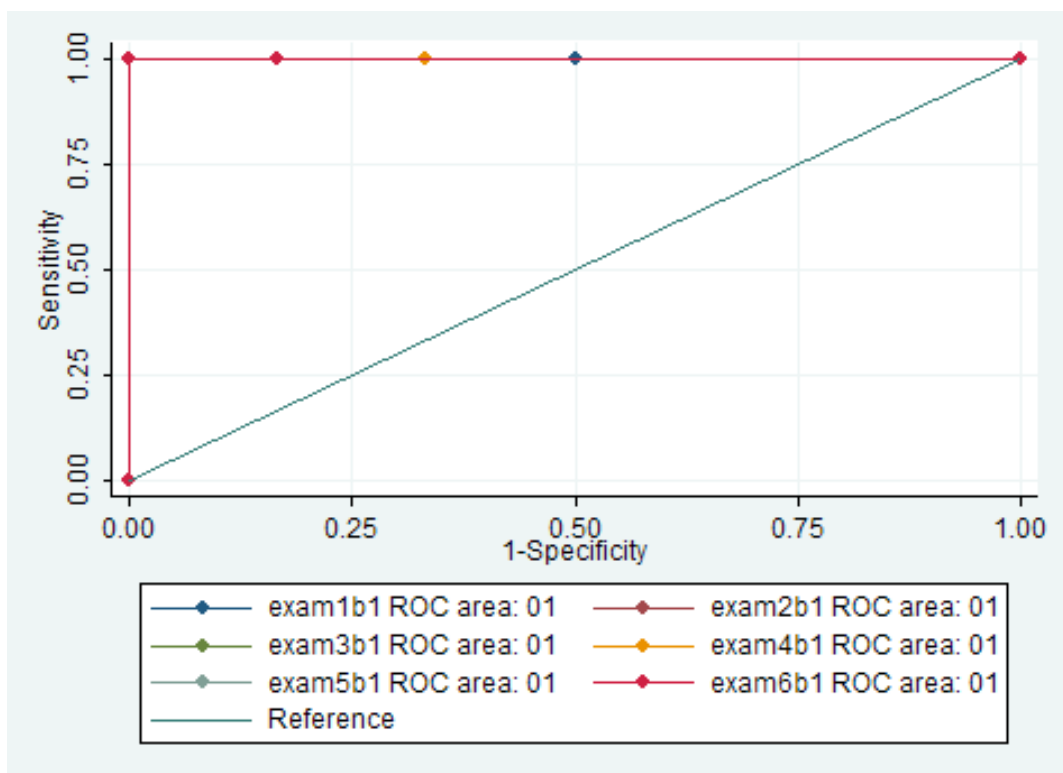
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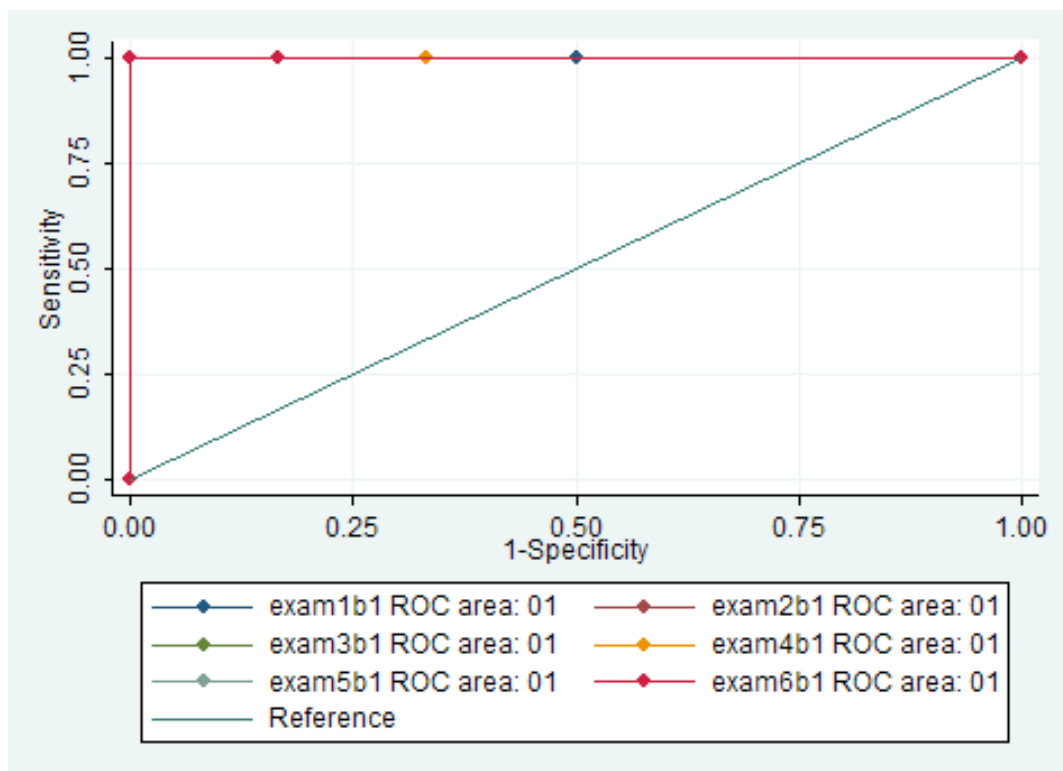
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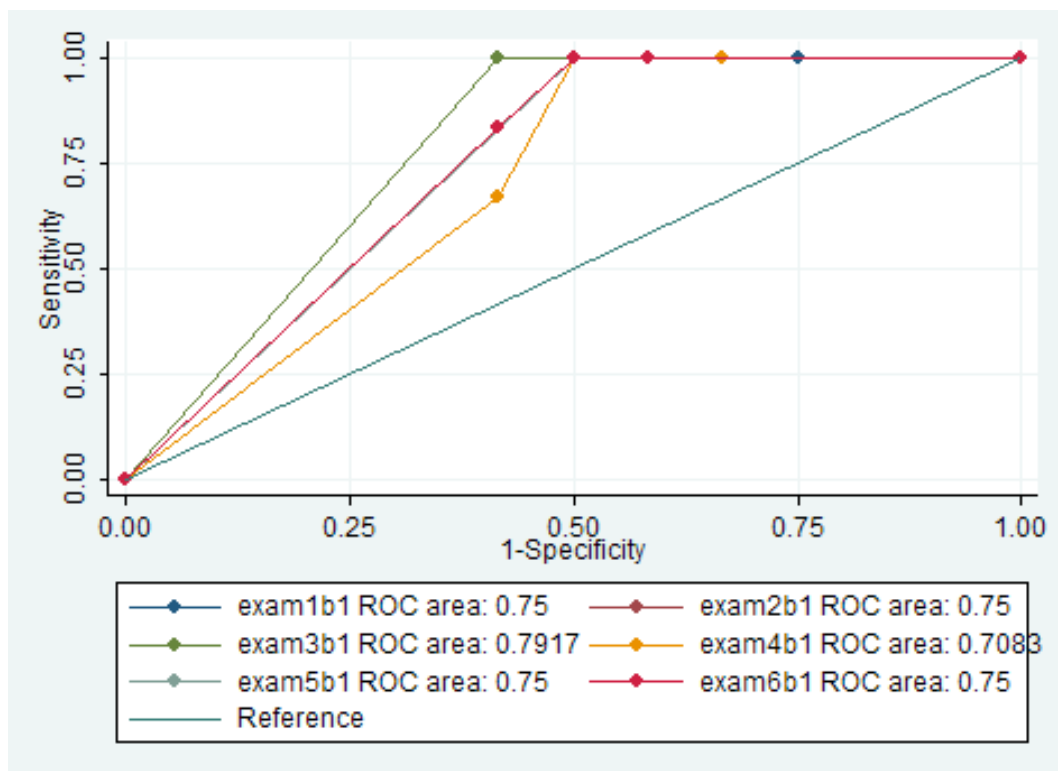
Receiver Operating Characteristic curves for no periapical lesions versus small (2mm) periapical lesions with CBCT.



Receiver Operating Characteristic curves for no periapical lesions versus large (4mm) periapical lesions with CBCT.

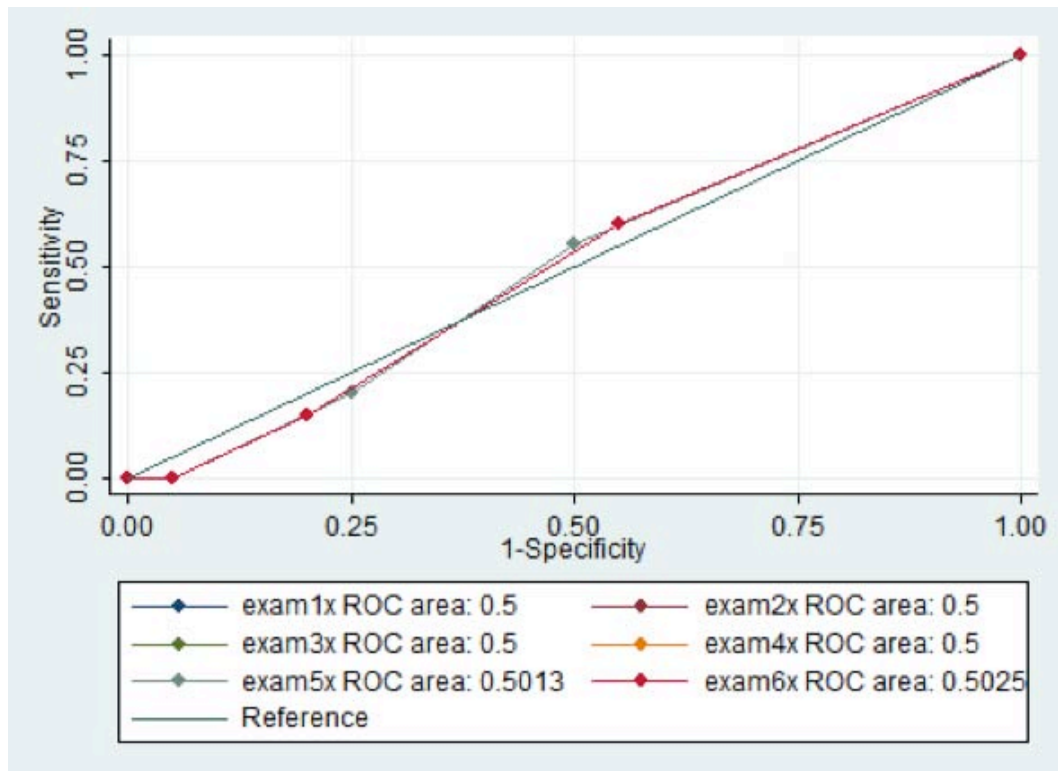


Receiver Operating Characteristic curves for no periapical lesion versus any (small or large) periapical lesion with CBCT.

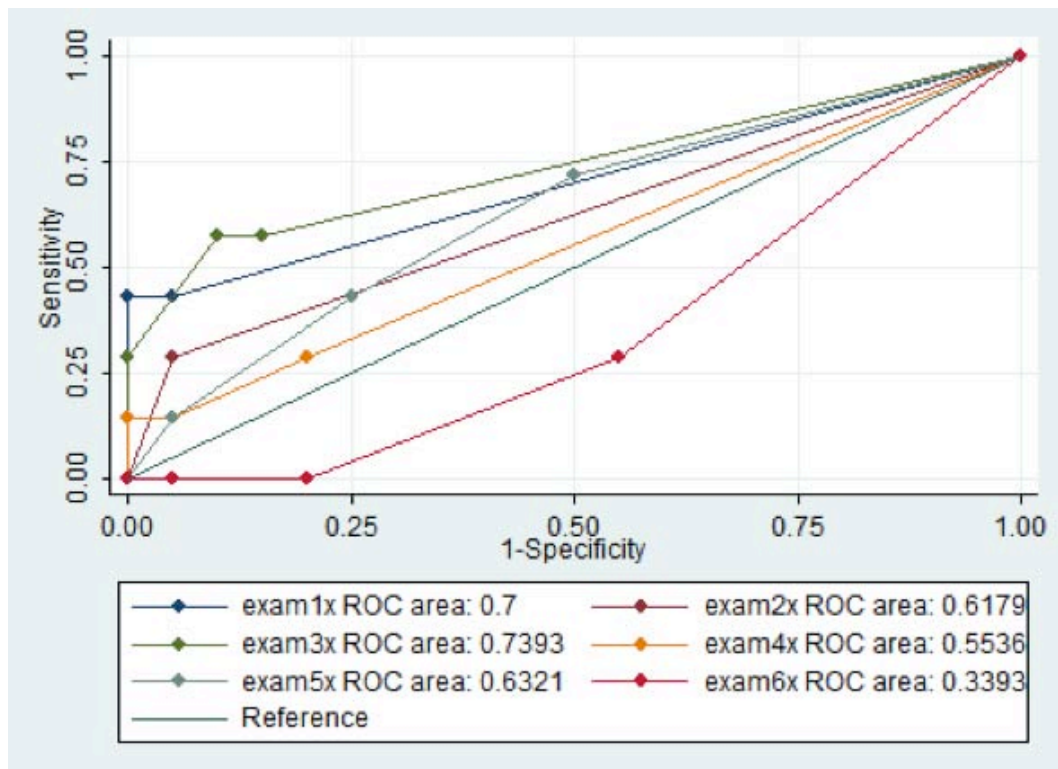


Receiver Operating Characteristic curves for no or small periapical lesions versus large periapical lesions with periapical radiograph.

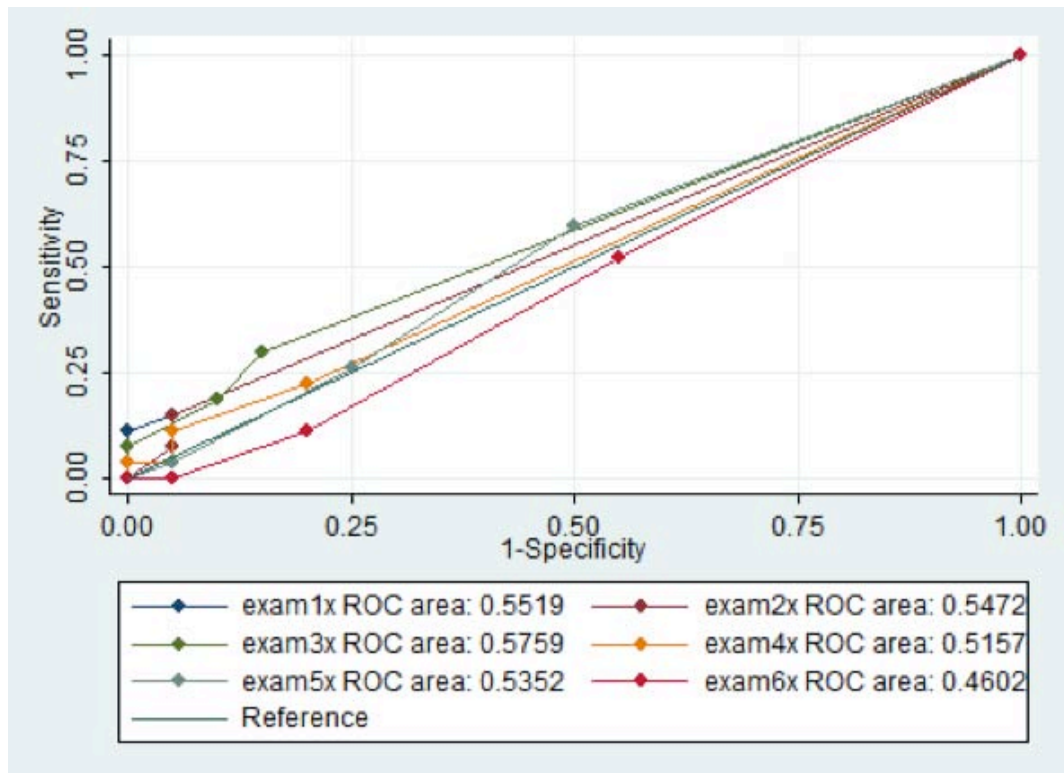
Appendix II



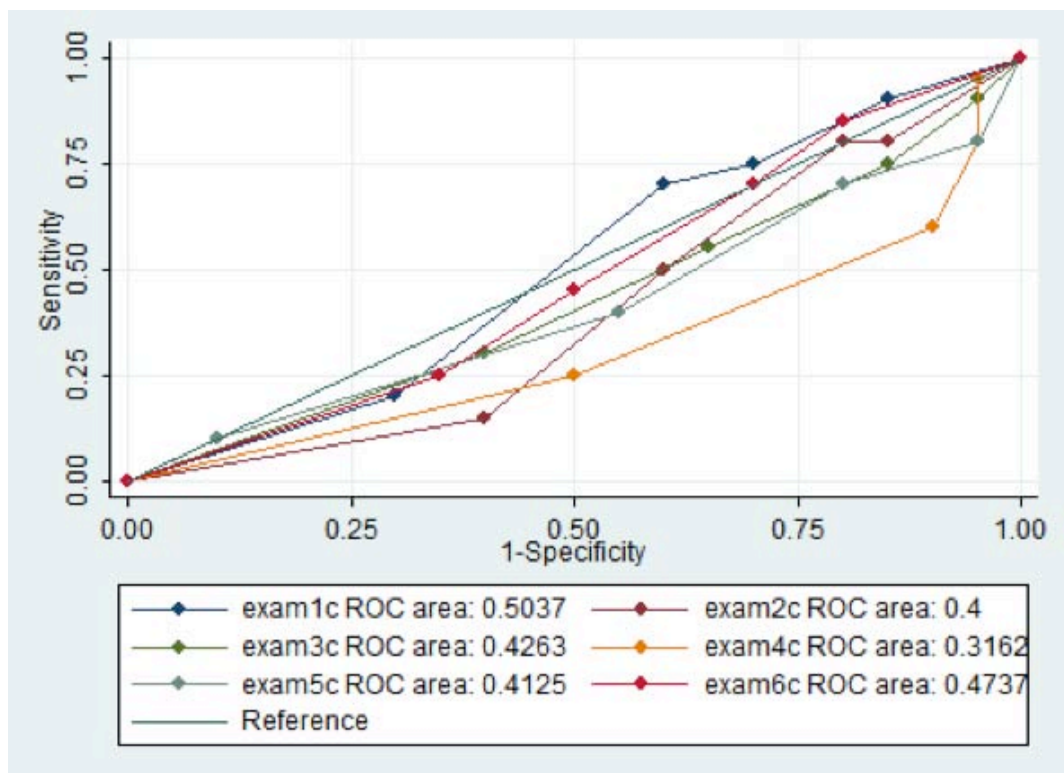
Receiver Operating Characteristic curve for no VRF versus incomplete VRF with periapical radiographs.



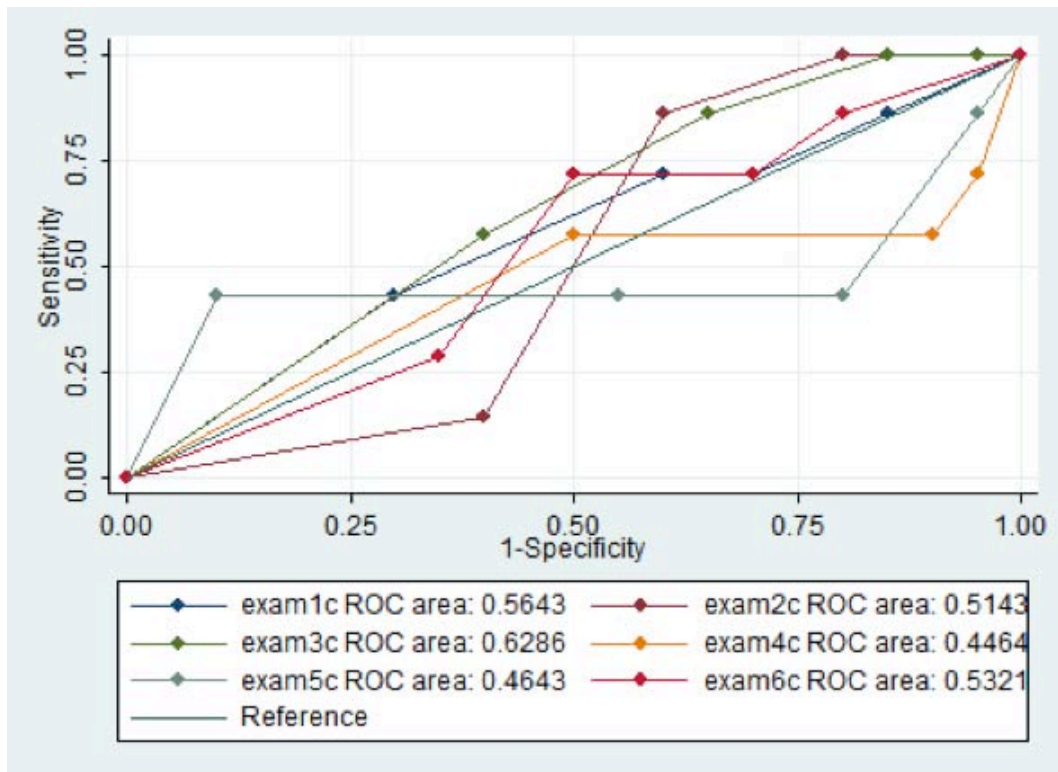
Receiver Operating Characteristic curve for no VRF versus complete VRF with periapical radiographs.



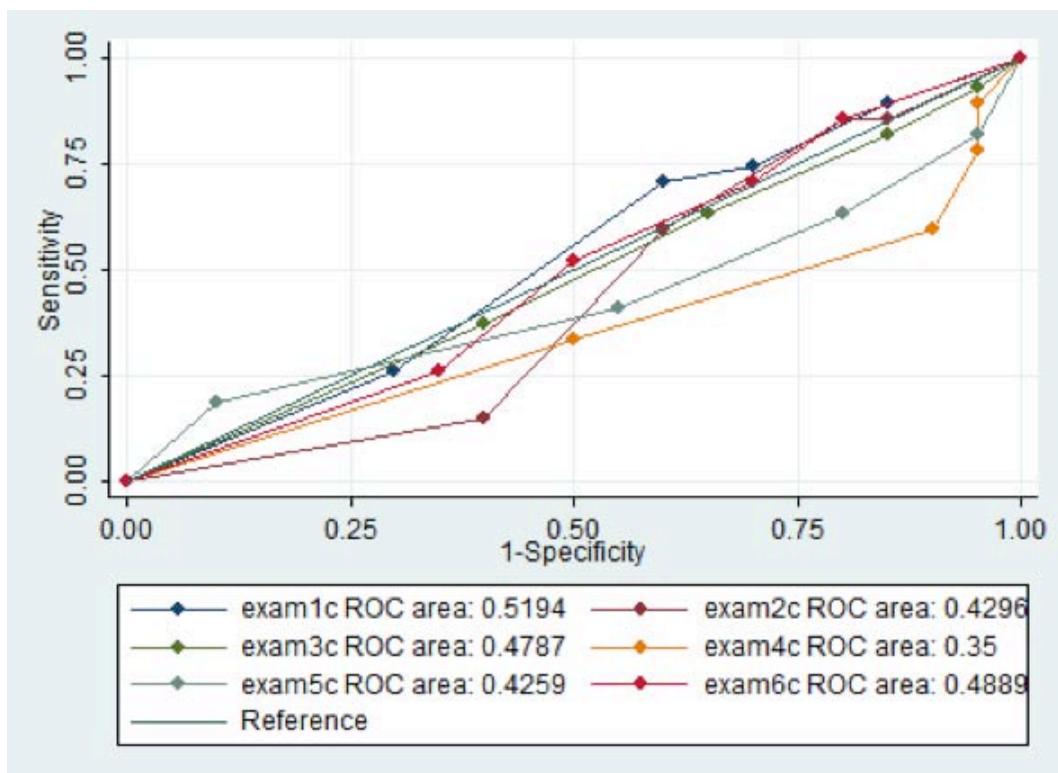
Receiver Operating Characteristic curve for no VRF versus any (incomplete or complete) VRFs with periapical radiographs.



Receiver Operating Characteristic curve for no VRF versus incomplete VRF with CBCT.



Receiver Operating Characteristic curve for no VRF versus complete VRF with CBCT.



Receiver Operating Characteristic curve for no VRF versus any (incomplete or complete) VRFs with CBCT.



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Filing Date*	:	23-Jun-2010	
Earliest Priority Date	:		
Applicant(s)/contact point	:	Andrew Dawood, Shanon Patel	
Application Fee Paid	:	No	Must be paid by 23-Jun-2011
Description (number of pages)	:	2	
Claims (number of pages)	:	3	
Drawings(number of pages)	:	None	
Abstract (number of pages)	:	None	Must be submitted by 23-Jun-2011
Statement of inventorship (Form 7)	:	No	
Request for search (Form 9A)	:	No	Must be submitted by 23-Jun-2011
Request for examination (Form 10)	:	No	
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1338 BALLAIGUES

A l'att. de M. Paul-Henri Vallotton

O/Ref: BFM/CM/ph/16017-PCT
"Matériau d'obturation 3D"

Geneva, August 24, 2011

Re : International patent application No PCT/IB2011/001444 filed on June 23, 2011
in the names of Dawood Andrew & Patel Shanon, claiming priority of British
patent application No 1010519.5 filed on June 23, 2010.

Dear Sir,

Further to our letter dated July 1st, 2011, we inform you having received from
Mr. Patel the requested priority document.

We confirm having filed this document at the WIPO in order to complete the
above-mentioned patent application.

We herewith enclose our debit note for the steps taken and will not fail to keep
you informed of the prosecution of this case.

In the meantime, we remain,

Yours Faithfully,
MICHELI & CIE SA

Bertrand MICHELI

Enclosures mentioned

Copy of this letter is sent to andrewdawood@hotmail.com and to
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A dental root canal obturation material

The present invention relates to a dental root canal obturation material for endodontics treatment.

5 Endodontics is the dental specialty that deals with the tooth pulp and the tissues surrounding the dental root of a tooth.

In the course of endodontic treatment, obturation of the dental root canal system with a dental root canal filling material after dental root canal disinfection is essential to prevent re-infection of the disinfected dental root canal space, entomb
10 remaining micro-organisms and prevent entry of periapical tissue fluid into the dental root canal space.

The following definition shall apply throughout the specification and the claims. Radiodensity or radiopacity (the two terms will be used indifferently) refer to the relative inability of electromagnetic radiation, particularly X-rays, to pass
15 through a particular material. Radiolucency indicates greater transparency or "transradiancy" to X-ray photons. Materials that inhibit the passage of electromagnetic radiation are called radiodense or radioopaque, while those that allow radiation to pass more freely are referred to as radiolucent. Radiopacity refers to the relatively opaque white appearance of dense materials or substances
20 on radiographic imaging studies, compared with the relatively darker appearance of less dense materials. The Hounsfield scale is a quantitative scale for describing radiodensity. However, in the following, radiopacity will be measured in mm Al/mm according to the norm ISO 6876:2003 which is the standard norm for endodontic dental root filling material. A material has a radiopacity of x mm Al/mm if 1 mm
25 thick of the said material has a radiopacity equivalent to x mm thick aluminium.

In medical imaging, artefacts are misrepresentations of tissue structures seen in medical images produced by modalities such as ultrasonography, X-ray computed tomography and magnetic resonance imaging. These artefacts may be caused by a variety of phenomena such as the underlying physics of the energy-

tissue interaction (for example ultrasound-air), data acquisition errors (such as patient motion), or a reconstruction algorithm's inability to represent the anatomy. There is a risk mistaking these artefacts for actual pathology if the practitioner doesn't recognize them.

- 5 It is commonly perceived that the specific characteristic of radiopacity of the dental root canal filling materials is desirable when obturating dental root canals. It is important to achieve firm condensation of the material against the dental root canal surface, and the radiopacity of the material allows the operator to visualise the material on the intra-oral radiograph and to an extent confirm that the material
10 fills the entire dental root canal system.

Radiographs may be taken of the treated tooth in the course of treatment, and for subsequent post operative follow-up visits. The presence of the radiodense material makes it possible to visualise the dental root canal filling material using two dimensional intra oral or plain film radiography, as the radiopaque filling
15 material is easily viewed against the background of the imaged dental root or bone. However, inevitably these two dimensional 'shadowgraphs' lack the three dimensional detail, and do not really adequately give the true picture of the dental root canal system, as they can't reveal void or extra canal for example.

- Three dimensional imaging of the jaws is becoming increasingly popular in
20 dental surgery environments. This is largely due to increasing access to Cone Beam Computed Tomography (CBCT) technology. CBCT is an example of a relatively low dose three dimensional imaging technique, which is rapidly gaining acceptance in endodontics. Access to, and further developments in this new technology, particularly in terms of dose reduction, mean that it will gain more
25 widespread and common usage in endodontic therapy.

Dental root canal systems often follow curving or complex courses making two dimensional radiographs very difficult to interpret. Three dimensional imaging and CBCT have offered an exciting new approach to endodontic diagnosis, and will reveal voids and extra canals.

However, the nature of the beam, the image acquisition and the reconstruction process of current CBCT imaging units lead to many imaging artefacts adjacent to a radiodense structure. Artefacts such as beam hardening, partial volume and photon starvation will lead to dark patches, bright streaks and dark bands. Highly radiodense structures will intensify these artefacts. Some software corrections are available. However their usefulness is limited, since their use induces a loss of detail around the radiopaque structure, which is often the area of interest for the diagnosis.

Gutta-percha based, and more recently polymer/resin based dental root canal fillings are common dental root canal filling materials used to obturate dental root canal systems. Radiopaque fillers, commonly in the form of metal salts, are used to impart radiopacity to these materials. Current dental root canal filling materials thus have a radiodensity of approximately 6 to 12 mm Al/mm, with the minimum fixed by the norm ISO 6876:2003 being 3 mm Al/mm.

This radiodensity of current obturation materials leads to strong artefacts while using techniques such as CBCT, which inhibits accurate diagnosis in the area of the dental root canal, particularly at the peripheral part of the radiodense material.

At present there is no obturation material specifically designed for use with three dimensional imaging systems alone, or in conjunction with current conventional radiographic systems. It is therefore the aim of the present invention to provide such a dental root canal obturation material optimised for visualisation and evaluation of endodontic results using three dimensional imaging technologies such as Cone Beam Computed Tomography (CBCT) and Computed Tomography (CT). Another aim of the present invention is to provide a dental root canal obturation material optimised for visualisation and evaluation of endodontic results using three dimensional imaging technologies that further allows for the material to be recognised using a traditional two dimensional imaging techniques to avoid

misdiagnosis from operator unaware that a dental root canal has been adequately treated.

To this end, there is provided a dental root canal filling material for endodontic treatment, characterised in that it comprises a central portion and a peripheral portion, the central portion having a higher radiopacity than the peripheral portion.

In the following, a central portion of a material will designate an internal portion of the material as opposed to a peripheral portion. Moreover, the use of the adjective "central" doesn't imply a particular shape or position. Thus, a central portion of the material could have any suitable shape at any position inside the material as long as it is not a peripheral portion.

An ideal material from the perspective of diagnosis and analysis with the aid of three dimensional radiographic imaging techniques would have a peripheral portion having a lower radiodensity, typically lying in the region of 1 to 3 mm Al/mm giving it a radiopacity lying between that of dense cortical bone, dentine (1 mm Al/mm) and enamel (1.8 mm Al/mm). Of course a radiopacity of 2 to 6 mm Al/mm would also reduce artefacts in the area of diagnostic, i.e. around the dental root canal walls and the said peripheral portion of the material compared to materials having a still more radiodense peripheral portion.

The radiopacity of the peripheral and central portion of an obturation material according to the invention can be adapted by adjusting the quantity of radiopacifiers (such as metal salts, tungsten) and the amount and type of fillers. The peripheral and/or central portions of the obturation material may consist of gutta-percha, other thermoplastic polymers or polyamides, combined with inorganic filler. The chemical composition of the filler can be used to adjust radiopacity of the central and/or peripheral portion of the obturation material, as well as radiopacifiers such as metal salts (barium salts, bismuth salts), oxides (zirconium oxide, bismuth oxide), or metals (tungsten).

Thus this invention provides for the incorporation of radiopaque components designed to impart a distinct 'signature' in a central portion of material. This signature will then be visible using a traditional two dimensional imaging technique and will help the practitioner recognise a treated tooth and the particular type of material that has been used. Moreover, different types of signature could highlight different types of obturation material: a first signature could indicate that traditional gutta-percha was used to treat the tooth, while a second signature could indicate that a thermoplastic polymer was used.

These radiopaque components may take the form of fine particles, strands, fibres, wires, formed objects, or any structure intended to be clearly recognizable, and also resolvable by the use of two dimensional 'conventional' radiographs.

Such structures combined into a central portion of a traditional obturation material will impart a distinct signature appearance when viewed in a radiograph. These signature structures must be sufficiently radiopaque to be visible with a two dimensional imaging technique, while a peripheral portion of the said obturation material remains radiolucent allowing for a good visualisation of the dental root canal surface without artefact with a three dimensional imaging technique.

This may be achieved by introducing strands of a more conventional form of dental root canal filling material formulation (for example, gutta-percha of standard radiopacity), into a central portion of a more radiolucent material. Such a combination might be used to create a 'cone' or 'point' also having a distinctive striped or variegated appearance. One preferred approach to manufacture would be to form a cone comprising of a relatively radiopaque central portion and an exterior peripheral portion of a relatively radiolucent material.

The following table highlights examples of quantitative description of the obturation material according to the invention:

Component	Weight [%]
Thermoplastic polymer	10 to 40
Oxide particulate filler	0 to 80
Radiopacifier	0 to 40
Radiopaque signature	0 to 40
Waxes/Additives	0 to 10
Colorant	0 to 10

Several preferred embodiments of the present invention will now be described with reference to the accompanying drawings in which:

Figure 1 is a cross-sectional view of a tooth illustrating its root canals, one of which being obturated by a dental root canal obturation material according to the invention.

Figure 2a is a cross-sectional view of a first embodiment of a dental root canal obturation material according to the invention.

Figure 2b is a cross-sectional view of a variant of the first embodiment of a dental root canal obturation material according to the invention illustrated in figure 2a.

Figure 3a is a cross-sectional view of a second embodiment of a dental root canal obturation material according to the invention.

Figure 3b is a cross-sectional view of a variant of the second embodiment of a dental root canal obturation material according to the invention illustrated in figure 3a.

Figure 4 is a cross-sectional view of a third embodiment of a dental root canal obturation material according to the invention.

Figure 1 is a cross-sectional view of a tooth 22 that has been endodontically prepared for root canal obturation by first removing a portion of the crown 23 to form an access opening 24. The access opening 24 permits the pulp and infected tissue (not shown) to be removed from the tooth and to expose the interior

portions of the root canals 25 (two in the tooth pictured in figure 2). The root canals 25 are then commonly subjected to mechanical shaping operations e.g. reaming, filing, to obtain a root canal 25 with relatively long and tapered walls 26. Prior to the introduction of an obturation material 10 into the canals 25, the said canals are
 5 irrigated with cleaning and etching solutions to remove the residual pulp and any dentin 27 dislodged from the tooth 22 during the mechanical shaping of the root canals 25. An obturation material 10 can then be introduced into the canals 25. The positioning of the obturation material 10 and the obturation procedure are well known to the skilled person of the art and will not be further described.

10 Some embodiments of a dental root canal obturation material according to the invention will now be described in further detail.

Figure 2a illustrates a first embodiment of a dental root canal obturation material according to the invention. The dental root canal obturation material is provided in the form of a cone 100 made preferably of gutta-percha or any other
 15 suitable thermoplastic polymer having a lower radiopacity than commonly used known obturation materials. Preferably, the radiopacity of the cone 100 is in the range of 1 to 6 mm Al/mm. According to this first embodiment, the said cone 100 contains a thin wire 102. The said wire 102 is preferably made of a biocompatible radiopaque metal and has a higher radiopacity than the radiopacity of the cone
 20 100. Preferably, the thin wire 102 has a radiopacity of 6 mm Al/mm or above. The thin wire 102 could be made of one of the following metals: titanium, titanium alloys, stainless steel, gold, cobalt, tungsten, nickel-titanium alloys, cobalt-chromium alloys or tantalum. In a variant, the thin wire 102 could also be a yarn of ceramic or glass having a radiopacity higher than the radiopacity of the cone 100.

25 The wire 102 is placed in a central portion 101 of the cone 100 and has preferably a diameter of 0.1 mm or less. The thin wire 102 acts like a characteristic signature and because it is more radiopaque than the cone 100, it will appear as a bright stripe in the darker radiolucent material of the cone and thus will be clearly recognisable using a two dimensional radiographic imaging technique. The thin

wire should be thick enough to be visible on a two dimensional X-ray image but should be thin enough so as not to create artefact in the area of diagnostic interest, i.e. the dental root canal surface 26 and a peripheral part of the cone 103, while using a three dimensional imaging technique.

5 In a variant of the first embodiment, illustrated in figure 2b the thin wire 102' has a helical shape. All the characteristics described above regarding the first embodiment are applicable.

Figure 3a illustrates a second embodiment of the invention. In this embodiment, the dental root canal obturation material has the form of a cone 110
10 that can be made of gutta-percha, thermoplastic polymers or polyamides for example. A central portion 112 of the cone is radiopaque. Preferably, the central portion has a radiopacity greater than 3 mm Al/mm and is made of gutta-percha combined with a radiodense filler, such as zinc oxide.

The cone 110 according to this second embodiment presents a peripheral
15 portion 111, which is the part of the obturation material that will be in contact with the dental root canal walls 26. The said peripheral portion 111 is less radiopaque than the central portion, having preferably a radiopacity lesser than 6 mm Al/mm. The peripheral portion 111 is preferably made of the same material as the central portion 112, such as gutta-percha, any other thermoplastic polymers or
20 polyamides but combined with a radiolucent filler such as magnesium oxide or calcium oxide.

Thus the more radiopaque central portion 112 of the cone 110 will be clearly visible using a two dimensional imaging technique while a less radiopaque peripheral portion 111 of the cone 110 will permit to obtain a clear three
25 dimensional image with no artefact in the area of diagnostic interest that is around the said peripheral portion 111 of the cone 110 and the dental root canal walls 26.

A variant of the second embodiment is illustrated in figure 3b. In this variant the central portion 112' of the cone 110 is made of gutta-percha, any other thermoplastic polymer or other suitable material. Preferably, in this variant, the

central portion 112' is made of the same material as the peripheral portion 111. The central portion is then made more radiopaque than the peripheral portion 111 by adding particles, strands or fibres 113 of a highly radiodense material. Preferably, these particles, strands or fibres 113 have a radiopacity of 3 mm

5 All/mm or above. They can be glass particles. The radiopacity of these particles strands or fibres 113 can be adjusted by adding metals such as titanium, chromium, barium, tantalum, lanthanum, tungsten or their oxides. Preferably, the size range of these fibres or particles 113 should be between 10 and 100 μ m.

(question: what size is that? Diameter? Length? width? More generally the

10 greatest dimension?) All the characteristics described above regarding the second embodiment are applicable. With this variant, the central portion will appear as a spotted portion using a two dimensional imaging technique, the particles strands or fibres 113 being clearly visible due to their high radiopacity.

Figure 4 illustrates a third embodiment of a dental root canal obturation

15 material according to the invention. In this embodiment, the dental root obturation material is a carrier based material 120 comprising a thermoplastic carrier 122. The carrier 122 comprises a handle 123 to facilitate manipulation and insertion of the obturation material 120 into the root canals 25. The handle 123 can be cut off or detached any other way once the carrier based obturation material 120 is

20 correctly positioned into the root canals 25. The thermoplastic carrier 122 is preferably made of a thermoplastic polymer like vulcanised rubber.

On the thermoplastic carrier 122 is coated an obturation material 121 such as gutta-percha, a thermoplastic polymer or a polyamide or any other suitable material. The thermoplastic carrier 122 is radiopaque having a higher radiopacity

25 than the obturation material 121. For example, the thermoplastic carrier 122 could contain radiopaque fillers or a radiodense signature such as the thin wire 102 or the particles or fibres 113 described above. The obturation material 121 can be combined with some radiolucent filler so that the said material 121 is less radiopaque than the carrier 122. Hence, the carrier 122 acts as a signature and

will be clearly visible using a two dimensional imaging technique, while the presence of artefact closer to the dental root canal walls 26 will be reduced using a three dimensional imaging technique.

The list of suitable substances that can be used to make an obturation material according to the invention mentioned above and comprising gutta-percha, thermoplastic polymer and polyamides is not exhaustive. It will be evident to the skilled person of the art that any suitable substance can be used as a base component of an obturation material according to the invention.

Other components without influence on radiopacity of the material such as colorants can be added to the obturation material according to the invention. In particular, particles of bioactive glass can be added, preferably to the peripheral portion of an obturation material according to the invention since these particles are known to promote bone growth.

Although several embodiments of a dental root canal obturation material according to the invention have been described, they all share the same essential characteristics and advantages. A dental root canal obturation material according to the invention presents at least a central portion that is more radiopaque than a peripheral portion of said material. Preferably, the peripheral portion which is substantially radiolucent has a radiopacity of 1 mm Al/mm to 6 mm Al/mm, while the radiopaque central portion has a radiopacity of 3 to 12 mm Al/mm. Although all described embodiments comprise a central portion extending substantially along the longitudinal axis of the obturation material, it is clear that the central more radiopaque portion of the obturation material according to the invention can have any suitable form allowing it to fulfil its purpose: being visible using a two dimensional imaging technique and being more radiopaque than a peripheral portion of the material to not create artefacts in the area of diagnostic interest using a three dimensional imaging technique.

Hence, the central radiopaque portion of the obturation material according to the invention acts like a signature indicating immediately to a practitioner if a

dental root canal has been treated and can provide detail on the particular obturation material used. On the other hand, the low radiopacity of a peripheral portion of the said material will allow the practitioner to clearly visualise the material in the area adjacent to the dental root canal walls 26, which is the area of

5 diagnostic interest.

CLAIMS

1. Dental root canal filling material for endodontic treatment,
5 characterised in that it comprises a central portion (101, 112, 112', 122) and a peripheral portion (103, 111, 121), the central portion (101, 112, 112', 122) having a higher radiopacity than the peripheral portion (103, 111, 121).

2. Dental root canal filling material according to claim 1, characterised
10 in that the said central portion has a radiopacity greater than 3 mm Al/mm.

3. Dental root canal filling material according to claim 2, characterised
in that the said central portion has a radiopacity comprised between 6 and 12 mm
Al/mm.

15 4. Dental root canal filling material according to any of the preceding claims, characterised in that the peripheral portion has a radiopacity comprised between the radiopacity of dense cortical bone and the radiopacity of enamel.

20 5. Dental root canal filling material according to claim 1, characterised in that the said peripheral portion has a radiopacity comprised between 1 and 6 mm Al/mm.

6. Dental root canal filling material according to any of the preceding
25 claims, characterised in that it is manufactured in the shape of a cone (100, 110).

7. Dental root canal filling material according to any of the preceding claims, characterised in that the central portion consists of a wire (102, 102').

8. Dental root canal filling material according to claim 7, characterised in that the wire is made of a biocompatible radiopaque metal having a radiopacity greater than 3 mm Al/mm.
- 5 9. Dental root canal filling material according to claim 8, characterised in that the said biocompatible radiopaque metal is one of the following metals: titanium and its alloys, stainless steel, gold, cobalt, tungsten, nickel-titanium alloys, cobalt-chromium alloys or tantalum.
- 10 10. Dental root canal filling material according to claim 7, characterised in that the thin wire (102) consists of a yarn of glass or ceramic combined with a radiopaque filler.
11. Dental root canal filling material according to any one of claims 7 to
15 10, characterised in that the wire is about 0.1 mm thin or less.
12. Dental root canal filling material according to any one of claims 7 to 11, characterised in that the wire has a helical shape.
- 20 13. Dental root canal filling material according to claim 6, characterised in that the said cone (110) is made of a thermoplastic polymer or a polyamide, the said polymer or polyamide being combined with a radiopaque filler in the central portion (112) of the material to make the said central portion radiopaque.
- 25 14. Dental root canal filling material according to claim 13, characterised in that the radiopaque filler is zinc oxide.
15. Dental root canal filling material according to claim 6, characterised in that the said cone (110) is made of a thermoplastic polymer or a polyamide,

radiopaque particles, strands or fibres (113) being incorporated to the said polymer or polyamide in the central portion (112) of the material to render the said portion radiopaque.

5 16. Dental root canal filling material according to claim 15, characterised in that the said radiopaque particles, strands or fibres (113) are glass particles combined with a radiopaque metal.

10 17. Dental root canal filling material according to claims 15 or 16, characterised in that the size of the said particles, strands or fibres (113) is between 10 and 100 μ m.

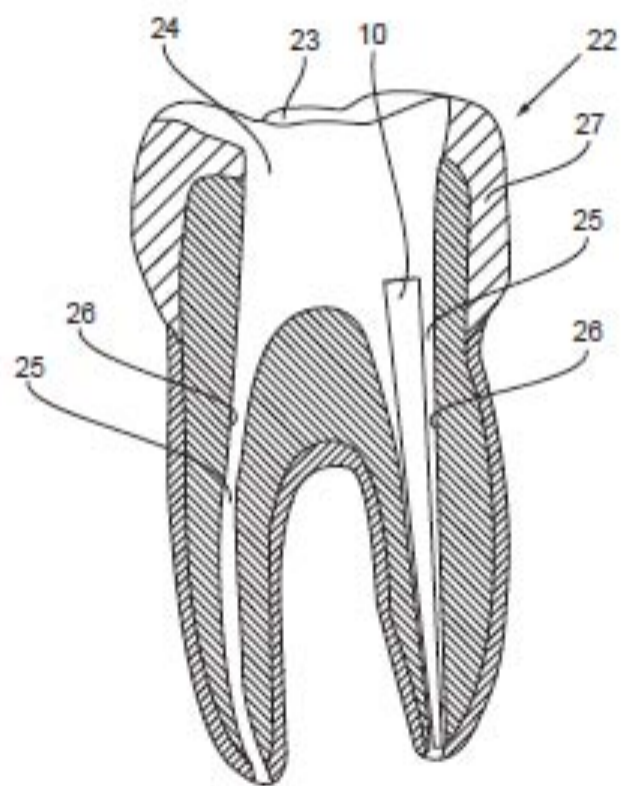
15 18. Dental root canal filling material according to any of claims 1 to 5, characterised in that it comprises a thermoplastic carrier (122) on which is coated an obturation component (121) and in that the central portion of the material consists of the thermoplastic carrier (122) and in that the peripheral portion of the material consists of the obturation component (121).

Abstract

The present invention relates to a dental root canal filling material for endodontic
5 treatment, characterised in that it comprises a central portion (101, 112, 112', 122)
and a peripheral portion (103, 111, 121), the central portion (101, 112, 112', 122)
having a higher radiopacity than the peripheral portion (103, 111, 121). The said
peripheral portion of the material is thus optimised for visualisation using a three
dimensional imaging technique while the central portion provides a "signature" that
10 is visible using a traditional two dimensional imaging technique.

(Figure 1)

Fig.1



2/3

Fig.2a

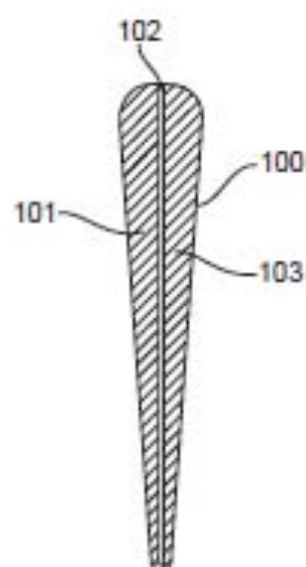


Fig.2b

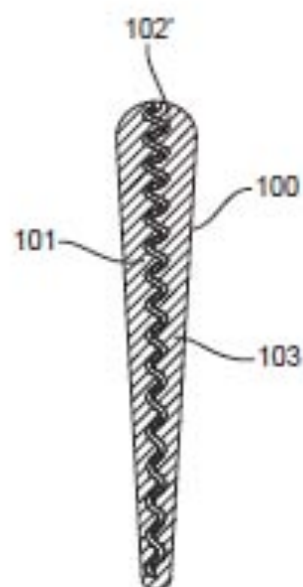


Fig.3a

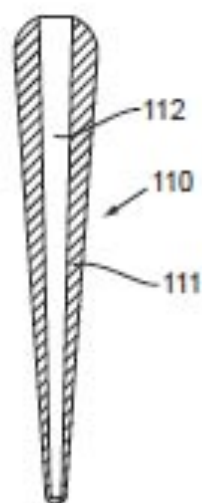


Fig.3b

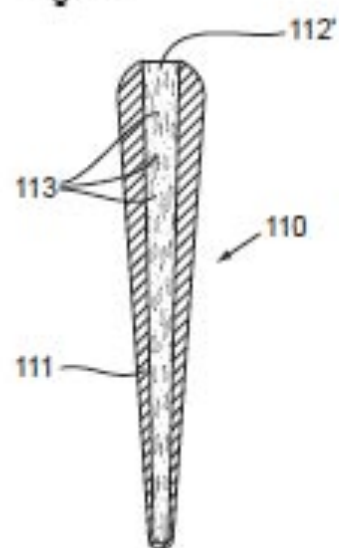
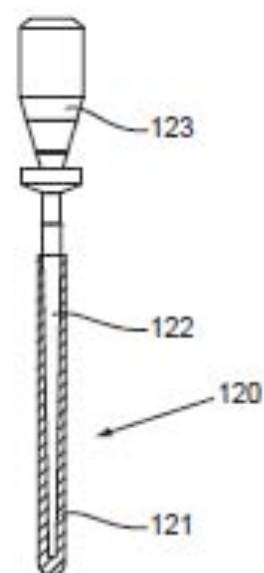


Fig.4



Appendix III



National Research Ethics Service

Guy's Research Ethics Committee

(South London REC Office 3)
Governor's Hall Suite
St Thomas' Hospital
SE1 7EH

Telephone: 020 7188 2260
Facsimile: 020 7188 2258

18 August 2008

Mr. Shanon Patel
Specialist Clinical Teacher
Endodontic Postgraduate Unit
Floor 25 Guy's Tower
Guy's Hospital

Dear Mr. Patel

Full title of study: Assessment of the outcome of endodontic treatment using cone beam computed tomography-A prospective study.
REC reference number: 08/H0804/79

Thank you for your letter of 12 August 2008, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Ethical review of research sites

The favourable opinion applies to the research sites listed on the attached form.

The Shanon Patel Endodontic Practice, Wimpole Street site also listed in the application does not require an SSA as the study is to be carried out entirely on non-NHS participants, using non-NHS premises or resources.

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

Management permission at NHS sites ("R&D approval") should be obtained from the relevant care organisation(s) in accordance with NHS research governance arrangements.

This Research Ethics Committee is an advisory committee to London Strategic Health Authority
The National Research Ethics Service (NRES) represents the NRES Directorate within
the National Patient Safety Agency and Research Ethics Committees in England

Guidance on applying for NHS permission is available in the Integrated Research Application System or at <http://www.rdforum.nhs.uk>.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application	SSI Form	04 June 2008
Application	Parts A & B	04 June 2008
Investigator CV	Mr Shanon Patel	
Investigator CV	Professor T Pitt Ford 2007	
Protocol	1	23 April 2008
Participant Information Sheet	2	02 August 2008
Participant Consent Form	2	02 August 2008
Response to Request for Further Information		12 August 2008

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Now that you have completed the application process please visit the National Research Ethics Website > After Review

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website:

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nres.npsa.nhs.uk.

08/H0804/79

Please quote this number on all correspondence

With the Committee's best wishes for the success of this project

Yours sincerely


 **Ms Sarah Allen**
Acting-Chair

Email: stephanie.hill@gstt.nhs.uk

Enclosures:

"After ethical review – guidance for researchers"
Site approval form

Copy to:

Mr Keith Brennan
R & D Office, GSTFT

Guy's Research Ethics Committee

LIST OF SITES WITH A FAVOURABLE ETHICAL OPINION

For all studies requiring site-specific assessment, this form is issued by the main REC to the Chief Investigator and sponsor with the favourable opinion letter and following subsequent notifications from site assessors. For issue 2 onwards, all sites with a favourable opinion are listed, adding the new sites approved.

REC reference number:	08/H0804/79	Issue number:	1	Date of issue:	18 August 2008
Chief Investigator:	Mr. Shanon Patel				
Full title of study:	Assessment of the outcome of endodontic treatment using cone beam computed tomography-A prospective study.				
This study was given a favourable ethical opinion by Guy's Research Ethics Committee on 18 August 2008. The favourable opinion is extended to each of the sites listed below. The research may commence at each NHS site when management approval from the relevant NHS care organisation has been confirmed.					
Principal Investigator	Post	Research site	Site assessor	Date of favourable opinion for this site	Notes ⁽¹⁾
Mr. Shanon Patel	Specialist Clinical Teacher	(GSTFT) Guy's and St Thomas NHS Foundation Trust St Thomas' Street Guy's Hospital London SE1 9RT	Guy's Research Ethics Committee	18/08/2008	
<p>Approved by the Chair on behalf of the REC:</p> <p><i>[Signature]</i> (Signature of Chair/Co-ordinator)</p> <p>(delete as applicable)</p> <p>.....STEPHANIE HILL..... (Name)</p>					

(1) The notes column may be used by the main REC to record the early closure or withdrawal of a study (where notified by the Chief Investigator or sponsor), the suspension of termination of a favourable opinion for an individual site, or any other relevant development. The date should be recorded.

REC Study Number: 08/H0804/79
Patient Identification Number for this trial:

PATIENT INFORMATION (version 3 15/10/2008)

Title of investigation: Cone beam computed tomography study 2

Name of Researcher: Mr. Shanon Patel

You are being invited to take part in a research study. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of this study?

Dental radiographs (X rays) are usually taken immediately after completion of treatment and on a periodic basis (review appointments), usually after 1 and 2 years after treatment has been completed to assess how successful treatment has been. The amount of information gained from conventional dental radiographs is limited as the images produced are only 2 dimensional (like a photograph).

Immediately before root canal treatment is commenced and at your review appointments in addition to the conventional radiograph we would also like to take an additional specialised 3-dimensional scan of the tooth. This 3-dimensional scan is called a 'Cone Beam Computed Tomography scan' and is the latest technology for imaging teeth. It allows us to assess your tooth in *3-dimensions* and therefore generates potentially more useful information about your tooth including the degree of healing. This specialised Cone Beam CT scan may give us a better understanding of the anatomy of your tooth. Review appointments will also be arranged 1 and 2 years after the completion of your root canal treatment.

By taking 2 different types of images of your tooth (the conventional 2-dimensional radiograph and a 3-dimensional limited Cone Beam Computed Tomography scan) and comparing them we are aiming to scientifically confirm that this new 3-dimensional scanning technique is more accurate and helpful in assessing healing of root canal treatment.

The additional scan will be taken straight after the conventional radiograph, and therefore will only add another 5-10 minutes to your appointment. The additional radiation dose from this second scan is minimal and is very similar to the conventional radiograph.

Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Do I have to take part?

It is up to you to decide. We will describe the study and go through this information sheet, which we will then give to you. If you agree to take part in the study we will then ask you to sign a consent form to show you have agreed to take part. You are free to withdraw at any time, without giving a reason. This would not affect the standard of treatment you receive.

What are the other possible disadvantages and risks of taking part?

The chance of any harm occurring to the patient as a result of exposure to dental X ray radiation is very small.

The effective dose of a cone beam computed scan is equivalent to less than 1 day of annual background radiation, so for the whole study the three extra scans are equivalent to less than 3 days of background radiation. To put this in perspective, the effective dose from cosmic radiation on board an aircraft flying a round trip from Paris to Tokyo is equivalent to 15 days of annual background radiation.

What are the possible benefits of taking part?

The specialised 'Cone Beam Computed Tomography scan' could allow us to accurately and objectively assess how successful your treatment has been.

What will happen to the results?

The results of this study will be presented at national and international scientific meetings, and also published in dental journals.

Who is funding this study?

This study is being funded by the Department of Restorative Dentistry.

Will my taking part in this study be kept confidential?

Each patient will be given a unique identification number which will be used throughout the study. Only authorised people will have access to your records, they will have a duty of confidentiality to you as a research participant and we will do our best to meet this duty.

The information we collect will be kept securely for seven years, after which it will be disposed of securely.

What if there is a problem?

If you have a concern or any questions about any aspect of this study, you should ask to Mr Shanon Patel who will do his best to answer your questions. If you remain unhappy and wish to complain formally, you can do this through the NHS Complaints Procedure.

Contact details:

Mr Shanon Patel Endodontic Unit, Floor 25 Guy's Tower, Guy's Hospital, London, SE1 9RT tel 020 7188 1605)

REC Study Number: 08/H0804/79
Patient Identification Number for this trial:

CONSENT FORM

(version 3 15/10/2008)

Title of Project: Cone beam computed tomography study 2

Name of Principle investigator: Mr. Patel

Please initial box

1. I confirm that I have read and understand the information sheet (Version 2 dated 2/8/2008) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I understand that sections of any of my medical notes may be looked at by responsible individuals from [company name] or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records. ☐
4. I agree to take part in the above study. ☐

Name of Patient	Date	Signature
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Name of Person taking consent (if different from researcher)	Date	Signature
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Researcher	Date	Signature
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1 for patient; 1 for researcher; 1 to be kept with hospital notes

Appendix IV



09 April 2008

National Research Ethics Service

Mr. Shanon Patel
Specialist Clinical Teacher
Endodontic Postgraduate Unit
Floor 25 Guy's Tower
Guy's Hospital

Guy's Research Ethics Committee

(South London REC Office 3)
Governors' Hall Suite
St Thomas' Hospital
SE1 7EH

Chair: Professor Steven H. Sacks
REC Co-ordinator: Stephanie Hill
Direct Line: 020 7188 2260
Email: stephanie.hill@gstt.nhs.uk
Website: www.nres.npsa.nhs.uk

Dear Mr. Patel

Full title of study: Assessment of peri-radicular endodontic lesions using
Cone beam computed tomography
REC reference number: 08/H0804/17

Thank you for your letter of 09 April 2008, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised.

Ethical review of research sites

The favourable opinion applies to the research sites listed on the attached form.

Conditions of approval

The favourable opinion is given provided that you comply with the conditions set out in the attached document. You are advised to study the conditions carefully.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application	Parts A & B	21 January 2008
Application	SSI Form	23 January 2008
Application	Part B Section 3	02 April 2008
Investigator CV	Professor Pitt Ford (Supervisor)	
Investigator CV	Shanon Patel	
Protocol	1	05 December 2007
Participant Information Sheet	2	02 April 2008
Participant Consent Form	2	02 April 2008
Response to Request for Further Information		09 April 2008

This Research Ethics Committee is an advisory committee to London Strategic Health Authority
The National Research Ethics Service (NRES) represents the NRES Directorate within
the National Patient Safety Agency and Research Ethics Committees in England

R&D approval

All researchers and research collaborators who will be participating in the research at NHS sites should apply for R&D approval from the relevant care organisation, if they have not yet done so. R&D approval is required, whether or not the study is exempt from SSA. You should advise researchers and local collaborators accordingly.

Guidance on applying for R&D approval is available from
<http://www.rdforum.nhs.uk/rdform.htm>.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Now that you have completed the application process please visit the National Research Ethics Website > After Review

Here you will find links to the following

- a) Providing feedback. You are invited to give your view of the service that you have received from the National Research Ethics Service on the application procedure. If you wish to make your views known please use the feedback form available on the website.
- b) Progress Reports. Please refer to the attached Standard conditions of approval by Research Ethics Committees.
- c) Safety Reports. Please refer to the attached Standard conditions of approval by Research Ethics Committees.
- d) Amendments. Please refer to the attached Standard conditions of approval by Research Ethics Committees.
- e) End of Study/Project. Please refer to the attached Standard conditions of approval by Research Ethics Committees.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nationalres.org.uk.

08/H0804/17**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project

Yours sincerely



Professor Steven Sacks
Chair

Email: stephanie.hill@gstt.nhs.uk

Enclosures: *Standard approval conditions, SL-AC2*
 Site approval form

Copy to: R&D office, GSTFT

Guy's Research Ethics Committee

LIST OF SITES WITH A FAVOURABLE ETHICAL OPINION

For all studies requiring site-specific assessment, this form is issued by the main REC to the Chief Investigator and sponsor with the favourable opinion letter and following subsequent notifications from site assessors. For issue 2 onwards, all sites with a favourable opinion are listed, adding the new sites approved.

REC reference number:	08/H0804/17	Issue number:	1	Date of issue:	09 April 2008
Chief Investigator:	Mr. Shanon Patel				
Full title of study:	Assessment of peri-radicular endodontic lesions using Cone beam computed tomography				
This study was given a favourable ethical opinion by Guy's Research Ethics Committee on 09 April 2008. The favourable opinion is extended to each of the sites listed below. The research may commence at each NHS site when management approval from the relevant NHS care organisation has been confirmed.					
Principal Investigator	Post	Research site	Site assessor	Date of favourable opinion for this site	Notes ⁽¹⁾
Mr. Shanon Patel	Specialist Clinical Teacher	(GSTFT) Guy's and St Thomas NHS Foundation Trust St Thomas' Street Guy's Hospital London, SE1 9RT	Guy's Research Ethics Committee	09/04/2008	

Approved by the Chair on behalf of the REC:

 (delete as applicable) (Signature of Chair/Co-ordinator)

STEPHANIE HILL (Name)

(1) The notes column may be used by the main REC to record the early closure or withdrawal of a site (where notified by the Chief Investigator or sponsor), the suspension of termination of the favourable opinion for an individual site, or any other relevant development. The date should be recorded.

REC Study Number: 10/H0804/11
Patient Identification Number for this trial:

PATIENT INFORMATION (version 1 4/1/2010)

Title of investigation: Cone beam computed tomography study 3

Name of Researcher: Mr. Shanon Patel

You are being invited to take part in a research study. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of this study?

X ray imaging (for example, dental x rays and cone beam CT scans) are used to diagnose problems with teeth. This information can be more objective than relying on the patient's symptoms and clinical signs. However, conventional dental x rays are unable to detect early signs or causes of dental disease. This is partly due to the inherent problems with conventional radiography, these problems include obscuring the site of interest by overlying anatomy (anatomical noise), difficulty in positioning radiographs accurately and the compression of 3 dimensional information into a 2 dimensional shadowgraph (i.e. like a photograph), these factors may mask what is actually occurring in the area being assessed. In this respect the Cone Beam CT scan may be more accurate at detecting the true dental problem.

As we have already advised you, the detailed clinical examination we have carried out has confirmed that your tooth is unsalvageable. Ideally, to prevent you suffering from any symptoms or/ to alleviate your symptoms the tooth in question should be extracted. After the tooth is extracted, we would like to examine it under high magnification. The purpose of this is to compare how the true cause of failure (for example, dental decay or a fractured root) compares to the information gleaned from your dental X rays and cone beam CT scan.

Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Do I have to take part?

It is up to you to decide. We will describe the study and go through this information sheet, which we will then give to you. If you agree to take part in the study we will then ask you to sign a consent form to show you have agreed to take part. You are free to withdraw at any time, without giving a reason. This would not affect the standard of treatment you receive.

What are the other possible disadvantages and risks of taking part?

The extracted tooth will be prepared for high magnification analysis.

What are the possible benefits of taking part?

The research should allow us understand your dental problem in more detail, this in turn will improve our diagnosis and management of your dental problem.

What will happen to the results?

The results of this study will be presented at national and international scientific meetings, and also published in dental journals.

Who is funding this study?

This study is being funded by the Department of Restorative Dentistry.

Will my taking part in this study be kept confidential?

Each patient will be given a unique identification number which will be used throughout the study. Only authorised people will have access to your records, they will have a duty of confidentiality to you as a research participant and we will do our best to meet this duty.

The information we collect will be kept securely for seven years, after which it will be disposed of securely.

What if there is a problem?

If you have a concern or any questions about any aspect of this study, you should ask to Mr Shanon Patel who will do his best to answer your questions. If you remain unhappy and wish to complain formally, you can do this through the NHS Complaints Procedure.

Contact details:

Mr Shanon Patel Endodontic Unit, Floor 25 Guy's Tower, Guy's Hospital, London, SE1 9RT tel 020 7188 1605)

REC Study Number: 10/H0804/11
Patient Identification Number for this trial:

CONSENT FORM

(version 1 1/1/2010)

Title of Project: **Cone beam computed tomography study 3**

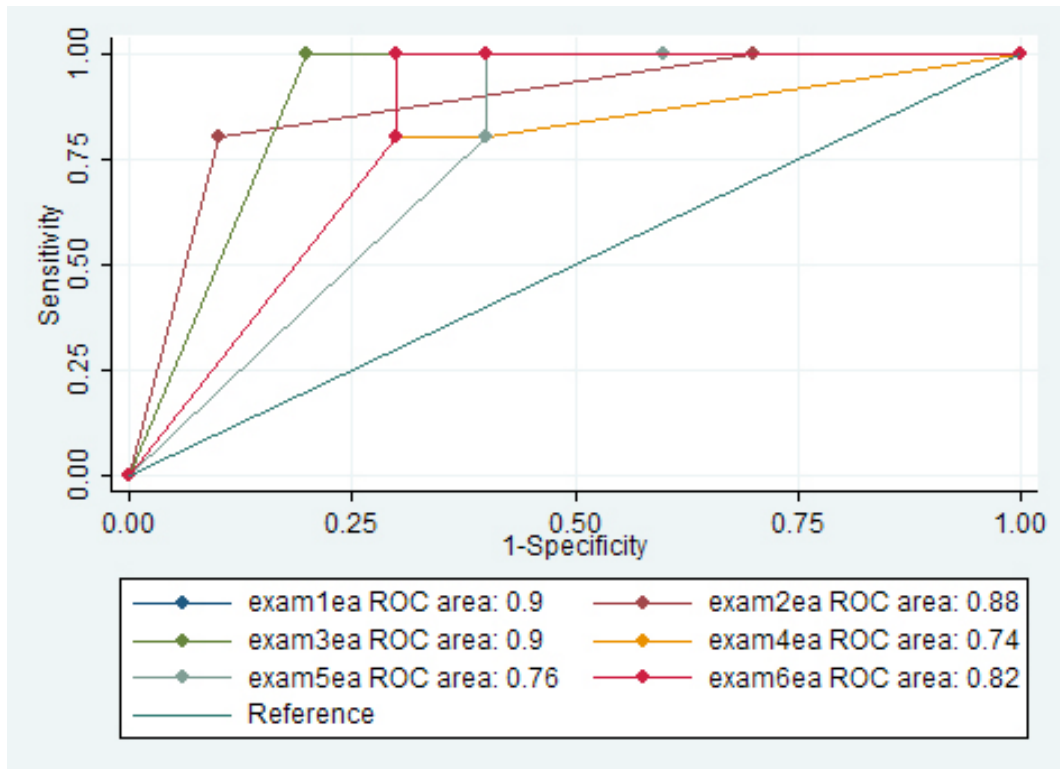
Name of Principle investigator: Mr. Patel

Please initial box

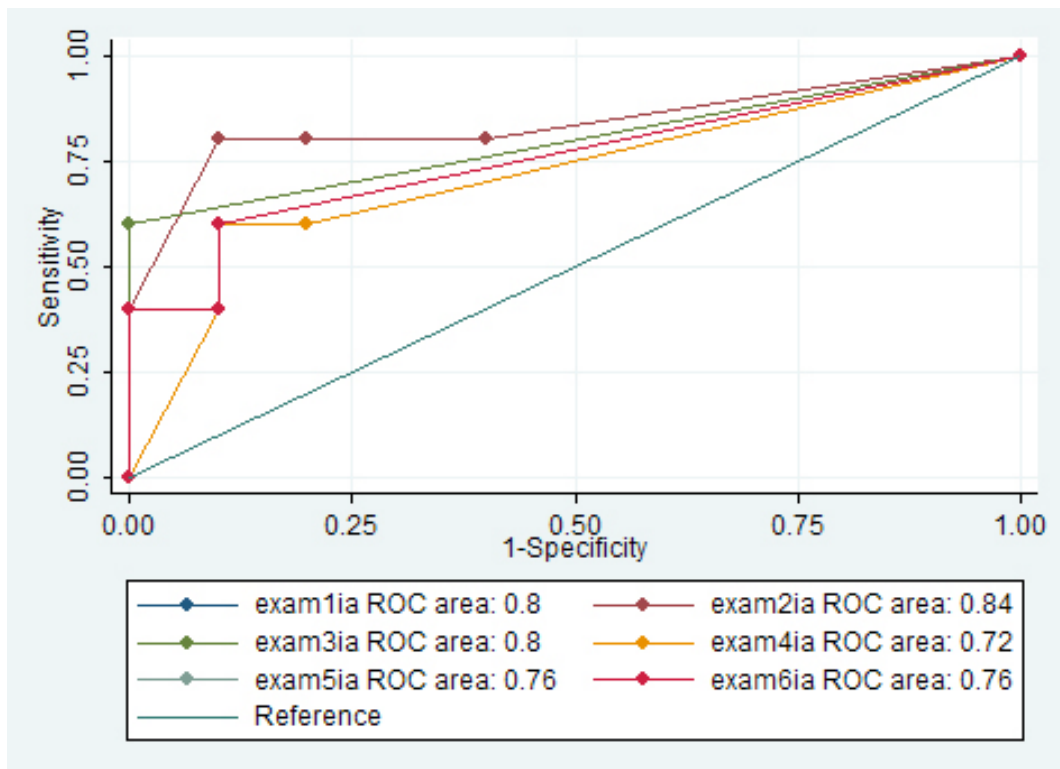
1. I confirm that I have read and understand the information sheet (Version 2 dated 2 April 2008) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I understand that sections of any of my medical notes may be looked at by responsible individuals from [company name] or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records. ☐
4. I agree to take part in the above study. ☐

_____ Name of Patient	_____ Date	_____ Signature
_____ Name of Person taking consent (if different from researcher)	_____ Date	_____ Signature
_____ Researcher	_____ Date	_____ Signature

1 for patient; 1 for researcher; 1 to be kept with hospital notes



Receiver Operating Characteristic curves for no resorption lesions versus external cervical resorption with periapical radiographs.



Receiver Operating Characteristic curves for no resorption lesions versus internal resorption with periapical radiographs.

Appendix V

Editorials

Patel S, Horner K (2009) Editorial: The use of cone beam computed tomography in endodontics. *International Endodontic Journal* **42**, 755-6.

Patel S, Mannocci F, Shemesh H, Wu M-K, Wesselink P, Lambrechts P (2011) Radiographs and CBCT-time for a reassessment. *International Endodontic Journal* **44**, 887-8.

Original Research

Patel S, Dawood A, Mannocci F, Wilson R, Pitt Ford T (2009) Detection of periapical bone defects in human jaws using cone beam computed tomography and intraoral radiography. *International Endodontic Journal* **42**, 507-515.

Patel S, Dawood A, Wilson R, Horner K, Mannocci F (2009) The detection and management of root resorption lesions using intraoral radiography and cone beam computed tomography - an *in vivo* investigation. *International Endodontic Journal* **42**, 831-838.

Patel S, Wilson R, Dawood A, Mannocci F, (2012) The detection of periapical pathology using digital periapical radiography and cone beam computed tomography-part 1-pre-operative status. *International Endodontic Journal* **in press**.

Patel S, Wilson R, Foschi F, Dawood A, Mannocci F, (2012) The detection of periapical pathology using digital periapical radiography and cone beam computed tomography-part 2-1 year post treatment outcome. *International Endodontic Journal* **in press**.

Patel S, Brady E, Wilson R, Mannocci F, (2012) The detection of vertical root fractures in root filled teeth with periapical radiographs and CBCT scans. *International Endodontic Journal* **submitted for publication**.



EDITORIAL

The use of cone beam computed tomography in endodontics

Cone beam computed tomography (CBCT) is a major advance in the imaging of teeth and the maxillo-facial skeleton. Reconstructed CBCT images provide 3-dimensional information of the area under investigation in a matter of minutes, usually at a lower radiation dose than that from 'medical' Computed Tomography but usually higher than that associated with simple dental radiographic techniques. All dental specialities are exploring the use of CBCT for managing dental problems. This is reflected in the rising numbers of papers being published on CBCT, not least in the field of endodontics.

In endodontics, CBCT has been used for several applications, including periapical diagnosis, evaluation of root canal anatomy, assessment of resorption defects, suspected perforations and in planning endodontic surgery but, with isolated exceptions (Özen *et al.* 2009, Patel *et al.* 2009), few are properly validated studies of diagnostic accuracy. Instead, the literature is dominated by case reports and observational studies without a reference standard. There is a need for well designed, validated, studies to assess the use of CBCT for diagnosis and management of endodontic problems. Furthermore, greater emphasis is needed on quantifying the impact of CBCT images on management. Only one study appears to have measured this, suggesting that CBCT images may increase the likelihood of the correct treatment plan being chosen when root resorption was considered (Patel *et al.* 2009).

As with any imaging technique involving patient exposure to ionizing radiation, it is essential that the radiation dose is kept *As Low as Reasonably Achievable* (Farman 2005). Therefore, before prescribing a CBCT scan it is essential that the clinician can *justify* its use, i.e. what potential additional relevant information can a CBCT scan yield over and above conventional radiography which may ultimately improve the management of the potential endodontic problem?

When the decision has been made to expose the patient to a CBCT scan it is essential to *optimize* the patient radiation dose. The smallest field of view (FOV)

compatible with the clinical situation should be used where possible to lower radiation doses. As the resolution selected affects the radiation dose used, this variable also needs to be carefully selected. Not all CBCT equipment is the same in either radiation dose or image quality; these should be important considerations for the clinician considering purchase of a machine or referring patients to colleagues. Optimization is particularly important in children and adolescent patients, who are more sensitive to the stochastic effects of radiation.

It is essential to assess the entire FOV, not just the region of interest. Clinicians may be able to interpret the dento-alveolar anatomy in three-dimensions confidently; however, they may be unfamiliar with the anatomy beyond this region (for example, base of the skull or the nasal cavity). In these cases, and also in instances where the clinician feels he/she is out of their 'comfort zone' he/she must obtain the opinion from a suitably qualified Dental Maxillo-facial Radiologist (Dawood *et al.* 2009). At present CBCT is not taught in the undergraduate curriculum and very few endodontic postgraduate programmes have incorporated CBCT into their curricula. Therefore, clinicians considering using CBCT technology must undergo specific training to appreciate CBCT technology, radiography and radiology.

Cone beam computed tomography technology is improving at a rapid pace, as does its uptake. As with any new technology, early enthusiasm may lead to inappropriate use. In response to this risk, the European Academy of Dental and Maxillofacial Radiology (Horner *et al.* 2009) and the American Academy of Oral and Maxillofacial Radiology (Carter *et al.* 2008) have each developed some guidelines designed to set core standards for CBCT. Similarly, the need for research and standard-setting was recognized by the European Commission's Seventh Euratom Framework in financing a 42 month collaborative project Safety and Efficacy of a New and Emerging Dental X-ray Modality (SEDENTEXCT), the aim of which is to acquire

key information necessary for sound and scientifically based clinical use of CBCT. SEDENTEXCT has just released some provisional detailed guidelines on CBCT use, including in endodontics (<http://www.sedentext.eu/guidelines>).

Whilst it is essential that the endodontic speciality appreciates the potential value of three-dimensional images, it is just as important to recognize the limitations of CBCT for endodontic use. The enthusiasm for CBCT seen in the literature over the last few years may well be justified, but we should remain cautious and keep some scepticism for the time being. Only when there is an adequate body of excellent research validating the diagnostic accuracy and clinical impact of CBCT will we be able to make an informed judgement on its role in endodontics. In the meantime, every use of CBCT should be carefully justified and optimized.

S. Patel¹ & K. Horner²

¹Endodontic Postgraduate Unit, King's College London Dental Institute, London; and ²Department of Oral and Maxillofacial Radiology, School of Dentistry, University of Manchester, Manchester, UK
e-mail: shanonpatel@gmail.com

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EDITORIAL

Shanon Patel¹, Francesco Mannocci¹, Hagay Shemesh², Min-Kai Wu², Paul Wesselink² and Paul Lambrechts³

¹Department of Conservative Dentistry, King's College London Dental Institute, London, UK; ²Department of Cariology and Endodontology, ACTA, Amsterdam, the Netherlands; and ³Department of Dentistry, Section of Endodontology, K.U.Leuven, Leuven, Belgium

Radiographs and CBCT – time for a reassessment?

Well-designed prospective clinical studies are essential to determine the outcome of endodontic treatment. The results from these studies allow us to estimate the prognosis of various treatments, thus greatly assisting the patient to make an educated informed decision on the best treatment option for their unique endodontic problem.

In endodontics for nearly 100 years this assessment has been carried out with the aid of radiographs. Essentially, this radiological assessment of the presence or absence of a periapical radiolucency provides a more objective assessment of the endodontic status of the tooth than relying on the patient's history and clinical examination. However, radiographs are not infallible; 50 years ago, a classic study by Bender & Seltzer (1961) highlighted the fact that periapical lesions confined to the cancellous bone could not be detected predictably. In fact, the endodontic literature is replete with studies highlighting the limitations of conventional radiographs; these constraints include the compression of the complex three-dimensional anatomy into a two-dimensional shadowgraph, anatomical noise and geometric distortion. Ultimately, these deficiencies may result in the underestimation of the size or, in some cases, the complete radiographic absence of existing periapical pathosis (Bender 1997, Lofthag-Hansen *et al.* 2007, Paula-Silva *et al.* 2009a). In one recent study of root filled mandibular posterior teeth, 25.9% of periapical lesions detected with CBCT were not detected with intraoral radiographs (Bornstein *et al.* 2011).

Small volume cone beam computed tomography (CBCT) is a novel three-dimensional imaging system that overcomes all of these limitations. *Ex vivo* studies using reference standards have clearly highlighted the

superior accuracy of CBCT in detecting periapical lesions (Özen *et al.* 2009, Patel *et al.* 2009). More recently, *in vivo* studies have concurred with these findings. Paula-Silva *et al.* (2009b,c) intentionally infected root canals in dog's teeth, these teeth were then sub-divided into different groups; some groups were root filled, the others were left as positive and negative control groups. Six months post-treatment the dogs were killed and a histopathological examination of the periapical tissues was carried out. The periapical radiograph and CBCT assessments were compared to these histopathological findings, and the results from this study confirmed the superior accuracy of CBCT for detecting the presence and absence of apical periodontitis, as well as the poor sensitivity of periapical radiographs in detecting existing apical periodontitis. They also found that radiographs underestimated the size of periapical pathosis when compared to the histological reference standard.

This improved accuracy with CBCT comes at an increased radiation dose to the patient. The smallest field of view is the most relevant for endodontic imaging as this type of scan results in a significantly reduced effective dose to the patient (Loubele *et al.* 2009). It also reduces the amount of unnecessary anatomy being scanned and therefore having to be reported upon (Holroyd & Gulson 2009, Patel & Horner 2009). Furthermore, evidence is emerging to suggest that adjusting the exposure parameters away from the manufacturer's default settings reduces the effective dose without adversely affecting the diagnostic yield of the CBCT scan (Durack *et al.* 2011). A recent study found that there was no difference in the diagnostic yield of CBCT images for assessing periapical lesions when the arc of rotation of the CBCT scanner was reduced from 360° to 180°, thus halving the number of projection images and therefore reducing the radiation exposure to the patient (Lennon *et al.* 2011).

Correspondence: Shanon Patel, email: shanonpatel@hotmail.com

It is time for our speciality to re-evaluate the way we assess the outcome of root canal treatment. We should think seriously about using CBCT to assess the outcome of treatment in specific situations. For example, when comparing different treatment strategies (single versus multiple visit root canal treatment, or different preparation and/or instrumentation techniques) the increased accuracy of CBCT may highlight differences that could be of clinical relevance and otherwise may be overlooked by periapical radiography. Only then can we give our patients a true guide of the likely prognosis of endodontic treatment.

Finally, we have to acknowledge our patient's right to an informed choice, especially when other diagnostic means are inconclusive. In these cases it would be desirable, considering its diagnostic value and the limited radiation exposure, to suggest the use of CBCT to confirm the presence or absence of apical periodontitis.

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Detection of periapical bone defects in human jaws using cone beam computed tomography and intraoral radiography

S. Patel^{1,2}, A. Dawood², F. Mannocci¹, R. Wilson³ & T. Pitt Ford¹

¹Endodontic Postgraduate Unit, King's College London Dental Institute, London, UK; ²Specialist Practice, London, UK; and

³Department of Periodontology, King's College London Dental Institute, London, UK

Abstract

Patel S, Dawood A, Mannocci F, Wilson R, Pitt Ford T.

Detection of periapical bone defects in human jaws using cone beam computed tomography and intraoral radiography. *International Endodontic Journal*, 42, 507–515, 2009.

Aim To compare the diagnostic accuracy of intraoral digital periapical radiography with that of cone beam computed tomography (CBCT) for the detection of artificial periapical bone defects in dry human jaws.

Methodology Small and large artificial periapical lesions were prepared in the periapical region of the distal root of six molar teeth in human mandibles. Scans and radiographs were taken with a charged couple device (CCD) digital radiography system and a CBCT scanner before and after each periapical lesion had been created. Sensitivity, specificity, positive predictive values, negative predictive values and Receiver Operator Characteristic (ROC) curves as well as the reproducibility of each technique were determined.

Results The overall sensitivity was 0.248 and 1.0 for intraoral radiography and CBCT respectively, i.e. these techniques correctly identified periapical lesions in 24.8% and 100% of cases, respectively. Both imaging techniques had specificity values of 1.0. The ROC Az values were 0.791 and 1.000 for intraoral radiography and CBCT, respectively.

Conclusions With intraoral radiography, external factors (i.e. anatomical noise and poor irradiation geometry), which are not in the clinician's control, hinder the detection of periapical lesions. CBCT removes these external factors. In addition, it allows the clinician to select the most relevant views of the area of interest resulting in improved detection of the presence and absence of artificial periapical lesions.

Keywords: cone beam computed tomography, endodontic diagnosis, periapical lesions.

Received 21 September 2008; accepted 18 November 2008

Introduction

Chronic apical periodontitis is the localized inflammation of the periapical tissues caused by bacterial infection from within the root canal system and the surrounding dentine (Huomonen & Ørstavik 2002, Nair 2004). It can present radiographically as a periapical radiolucent lesion as a result of a localized inflammatory reaction to infection within the root canal system reducing the mineral density of the affected periapical bone (Bender 1982, Ørstavik & Larheim 2008). The ability of radio-

graphic systems to detect chronic apical periodontitis is essential in Endodontology for diagnosis, treatment planning, determination of outcome and epidemiological studies (Bender 1982, Patel *et al.* 2009, Ørstavik & Larheim 2008). At present, intraoral radiography is the technique of choice for diagnosing, managing and assessing endodontic disease (Lofthag-Hansen *et al.* 2007, Nair & Nair 2007, Patel *et al.* 2007), but it is well established that intraoral radiography is of limited use for detecting chronic apical periodontitis (Huomonen & Ørstavik 2002). Anatomical features (noise) immediately adjacent to the area of interest may result in poor contrast and therefore increased difficulty in assessing the periapical tissues. Several studies (Bender and Seltzer 1961, Pauls & Trott 1966, Schwartz & Foster

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1971) have concluded that artificially created periapical lesions in posterior region of dry jaws are not easily visualized on radiographs when confined to the cancellous bone (the area of interest), as it is masked by the more mineralized and therefore denser overlying cortical bone (i.e. the anatomical noise). Periapical radiolucent lesions are usually only diagnosed when there has been perforation or erosion of the overlying cortical plate. Regan & Mitchell (1963) came to similar conclusions after assessing the radiographs of 289 teeth in 27 human cadavers. Lee & Messer (1986) suggested that periapical lesions, which have been successfully detected when confined to the cancellous bone, may not be readily observed if the thickness of the cortical bone is increased, i.e. the anatomical noise increases resulting in less contrast between the area of interest (periapical lesion in cancellous bone) and overlying anatomical noise (cortical bone).

The cortical plate, which acts as anatomical noise, is also one of the reasons why the radiographic size of periapical lesions is under-estimated when compared with the actual size of the periapical lesion (Schwartz & Foster 1971, Shoha *et al.* 1974, Scarfe *et al.* 1999). Another factor which may influence the radiological size of the periapical lesion is the inability to take parallel radiographs in certain situations. This can cause geometric distortion that may result in an increase or decrease in the size of the periapical lesion, or even result in the inability to visualize periapical lesions (Bender & Seltzer 1961, Huuonen & Ørstavik 2002).

Tachibana & Matsumoto (1990) were one of the first groups to recognize the benefits of computed tomography in endodontics. Computed tomography (CT) has been used in the management of endodontic problems to overcome the limitations (anatomical noise and geometric distortion) of conventional radiography (Marmary *et al.* 1999, Velvart *et al.* 2001). However, CT imaging has several disadvantages. These include the high radiation doses and the cost of the scans, and access to CT scanners is limited to dedicated specialized radiography centres. Over the last two decades, cone beam computed tomography (CBCT) has been developed specifically to produce three-dimensional scans of the maxillo-facial skeleton (Arai *et al.* 1999, Mozzo *et al.* 1999). Essentially, there are two types of CBCT, large volume CBCT scanners have a large field of view allowing the entire maxilla and/or mandible to be scanned, whereas limited CBCT scanners have a smaller field of view (3–4 cm³). The smaller the field of view, the lower the radiation (with all other factors being equal). These limited CBCT scanners are better

for managing endodontic problems as only the relevant part of the jaw is scanned. CBCT's major advantage over CT scanners is the huge reduction in radiation exposure. This is due in part to rapid scan times, pulsed X-ray beams and sophisticated image receptor sensors (Cotton *et al.* 2007, Patel *et al.* 2007). Shortcomings of both CT and CBCT include poorer resolution, scattering and artefacts when compared with conventional radiography (Patel 2009, Patel *et al.* 2009).

Loftthag-Hansen *et al.* (2007) has compared CBCT scans with two-angled (parallax) periapical radiographs to assess the periapical status of posterior mandibular and maxillary teeth. The prevalence of periapical lesions associated with teeth with endodontic problems was 31% higher when CBCT was used. Estrela *et al.* (2008) compared the ability of panoramic and periapical radiographs with CBCT for the detection of apical periodontitis. Their results confirmed the apparent increased sensitivity of CBCT for detecting apical periodontitis. Similar findings have also been reported by Low *et al.* (2008). These clinical studies appear to presume that the radiological findings from CBCT represent the true status of the periapical tissues, i.e. that CBCT can be used as a 'gold standard' to detect the presence or absence of periapical disease. The captured CBCT data also reveal additional relevant information about root canal morphology and neighbouring anatomical structures (e.g. the maxillary sinus and mandibular nerve), the true nature and relationship of a periapical lesion to a root and the thickness of the cortical and cancellous plates (Low *et al.* 2008), which cannot be readily obtained from conventional radiological views. To date, there have been no studies correlating the radiological findings of CBCT with the actual features found within the human jaws.

The aim of the present study was to compare the diagnostic accuracy of CBCT with intraoral periapical radiography for the detection of artificially prepared periapical bone defects in dry human jaws.

Materials and methods

Subject material

Ten first molar teeth on six partially dentate intact human dry mandibles were used this study (Department of Anatomy and Human Sciences, King's College London, University of London). Each mandible was soaked for 90 min in warm water into which hand dish washing liquid (Fairy Liquid Original, Procter & Gamble, Weybridge, Surrey, UK) had been added to reduce

the surface tension of the bone therefore increasing its water absorption. This also increased the moisture content and the resilience of the dry mandibles for the subsequent extraction of teeth. Screening radiographs and CBCT scans were taken of each first molar tooth to identify existing periapical lesions.

Prosthetic dental wax (Ribbon Wax; Metrodent, Huddersfield, UK) was used as a soft tissue substitute. The wax was applied in layers. Radiographs and CBCT scans were taken after each incremental layer of wax had been applied and compared with equivalent *in vivo* views. The process was continued until the radiological appearance of the dry mandible was similar to the radiological appearance of patient's mandibular molars. Once the optimal thickness of wax had been determined, it was applied to all mandibles.

The crown of the first molar tooth was sectioned through the furcation separating the mesial and distal roots. The distal root was then atraumatically extracted. The base of the socket was inspected with the aid of a dental operating microscope (3 step entrée Dental Microscope; Global, St Louis, MO, USA) to confirm that it was intact. The root was then firmly replaced into the socket. Baseline radiographs and CBCT scans were taken. Four first molar teeth were not used (one had an existing periapical lesion and three were fractured as they were being extracted).

The distal root was then removed again and a spherical periapical lesion of 2 mm (small) in diameter was prepared by drilling a hole into the cancellous bone at the base of the extraction socket using a premeasured dental laboratory bur (No. 406702 Diadur® Carbide Cutter; Bracon Limited, Etchingham, UK) in a laboratory handpiece. The mandible was then soaked in warm soapy water again for 15 min and the root was then firmly re-implanted into its socket. Radiographs and CBCT scans were then taken. The process was repeated using a second bur to enlarge the existing periapical lesion to 4 mm in diameter (No. 406602 Diadur® Carbide Cutter; Bracon Limited). A fresh fillet of beef tightly wrapped in cling film was used to mimic the tongue in the mandible for CBCT scans.

Radiographic technique

Two jigs were made for each mandible, one to allow standardized reproducible radiographs to be taken with a dental X-ray machine (Planmeca Prostyle Intra, Helsinki, Finland) using a digital CCD (Schick Technologies, New York, NY, USA). A second jig was made for standardized images to be taken with the small volume

CBCT scanner (Veraviewpocs; J Morita Manufacturing, Kyoto, Japan). The angle (i.e. the border between the ramus and body) of each mandible was embedded in polyvinyl-siloxane impression material (President, Coltène AG, Altstätten Switzerland) mounted onto medium-density fibreboard board using cyanoacrylate adhesive (SuperGlue; The Original Super Glue Corporation, Rancho Cucamonga, CA, USA). Once set, each mandible could be removed and reinserted in exactly the same position into its own jig. The X-ray tube head and digital sensor were also secured into position using a similar technique. The X-ray tube head, digital sensor and mandible were aligned to allow radiographs to be exposed using the paralleling technique. A similar jig was made for each mandible to be exactly repositioned in the CBCT scanner. Exposure parameters of 66 kV, 7.5 mA and a 0.10 s were used for the intraoral radiograph and 80 kV, 3.0 mA and a 17.5 s scan for the CBCT scanner. CBCT data was reformatted to align the root axis with the vertical plane in the sagittal and coronal views. The brightness and contrast of all the acquired images was enhanced to improve visualization of the periapical lesions. All CBCT data was resliced (0.125 slice intervals and 1.5-mm slice thicknesses).

Radiological assessment

Six examiners (endodontists $n = 2$, endodontic post-graduates $n = 4$) individually assessed the radiographs and CBCT scans in the following sequence: session 1 – radiographs (including duplication to assess intra-observer agreement), session 2 – CBCT scans and session 3 – CBCT scans repeated (to assess intra-observer agreement).

The images were then randomly ordered in each session and viewed as a powerpoint presentation (Microsoft Corp, Seattle, WA, USA) on a laptop computer (Toshiba Portege R500-11Z, Tokyo, Japan) which had a screen pixel resolution of 1280×1024 . A CBCT image that best confirmed the presence or absence of a radiolucent periapical lesion in the sagittal and coronal planes was used as the starting point for each tooth observation. Examiners also had access to the raw CBCT data allowing them to scroll through any of the orthogonal scans. All images were assessed in a quiet dimly lit room. The examiners were trained using examples of clinical radiographs and CBCT images with and without the presence of periapical lesions before embarking on the assessment; a periapical lesion was defined as a radiolucency associated with the radiographic apex of the distal root of the mandibular first

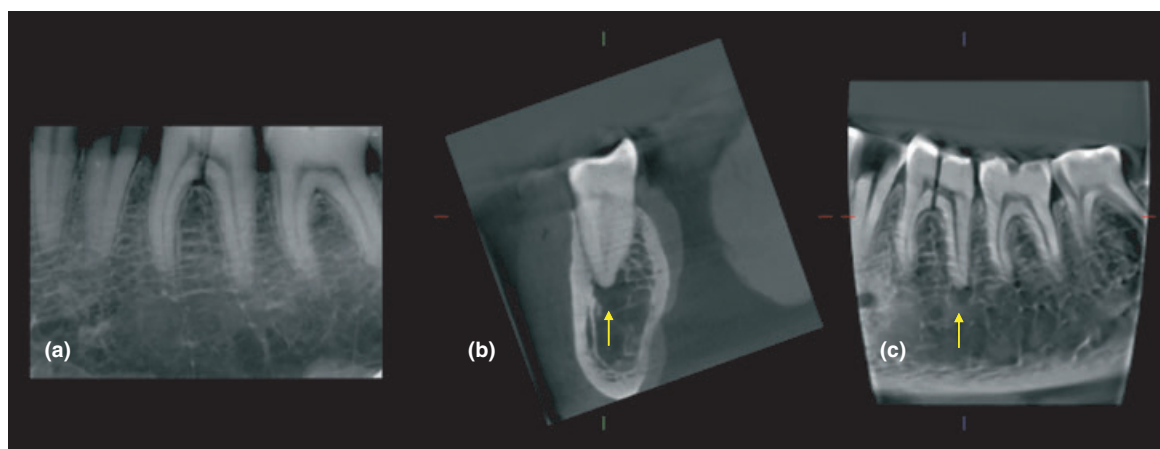


Figure 1 (a) Radiograph and (b) coronal and sagittal reconstructed cone beam computed tomography (CBCT) image of the same molar tooth. Note that an artificial lesion (yellow arrows) can be identified on the CBCT images but not on the periapical radiograph.

molar, which was at least twice the width of the periodontal ligament space (Fig. 1).

Examiners were asked to note down the presence or absence of a periapical lesion using a 5-point confidence scale as follows: 1 – periapical lesion definitely not present, 2 – periapical lesion probably not present, 3 – unsure, 4 – periapical lesion probably present and 5 – periapical lesion definitely present.

There was at least an interval of 1 week between each session. To assess intra-examiner validity for the radiographic assessment nine radiographs were repeated within session 1. Session 3 was used to assess intra-examiner validity for session 2.

Data analysis

Stata™ software (Stata 9, College Station, TX, USA) was used to analyse the raw data. Sensitivity, specificity and positive (PPV) and negative (NPV) predictive values were determined; Receiver Operating Characteristic (ROC) curve analysis was used to assess the diagnostic accuracy of each examiner and each imaging system for detecting the presence or absence of a periapical lesion. Inter-examiner and intra-examiner agreement was assessed by Kappa statistics for 50% of the intraoral radiographs and 100% of the CBCT scans.

Results

The overall sensitivity of intraoral radiography (0.248) was lower than CBCT (1.000) regardless of the size of the lesion ($P = 0.026$), i.e. these techniques correctly

Table 1 Mean (SD) values of sensitivity, specificity, PPV and NPV for radiograph and CBCT for detecting small periapical lesions

	Sensitivity	Specificity	PPV	NPV
Radiograph	0.2 (0.0)	1 (0.0)	1 (0.0)	0.545 (0.0)
CBCT	1*	1	1	1

SD, standard deviation; PPV, positive predictive value; NPV, negative predictive value; CBCT, cone beam computed tomography.

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity: $P = 0.014$.

Table 2 Mean (SD) of sensitivity, specificity, PPV and NPV for radiograph and CBCT for detecting large periapical lesions

Examiner	Sensitivity	Specificity	PPV	NPV
Radiograph	0.35 (0.16)	1 (0.0)	1 (0.0)	0.573 (0.03)
CBCT	1*	1	1	1

SD, standard deviation; PPV, positive predictive value; NPV, negative predictive value; CBCT, cone beam computed tomography.

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity: $P = 0.024$.

Table 3 Mean (SD) of sensitivity, specificity, PPV and NPV for radiograph and CBCT for detecting all periapical lesions

Examiner	Sensitivity	Specificity	PPV	NPV
Radiograph	0.248 (0.10)	1 (0.0)	1 (0.0)	0.384 (0.02)
CBCT	1*	1	1	1

SD, standard deviation; PPV, positive predictive value; NPV, negative predictive value; CBCT, cone beam computed tomography.

*Wilcoxon matched-pairs, signed-ranks test for differences in sensitivity: $P = 0.026$

Table 4 Area under the curve from ROC analysis of radiographs and CBCT for individual examiners: comparison of no defect with both small and large defects

Examiner	Radiograph	Cone beam	P-value
1	0.875	1.000	0.056
2	0.917	1.000	0.138
3	0.708	1.000	<0.001
4	0.764	1.000	0.025
5	0.708	1.000	<0.001
6	0.771	1.000	0.020
Mean (SD)	0.791 (0.087)	1.000 (0.000)	0.027*

SD, standard deviation; ROC, Receiver Operator Characteristic; CBCT, cone beam computed tomography.

*P-value from Wilcoxon matched-pairs, signed-ranks test.

Table 5 Area under the curve from ROC analysis of radiographs and CBCT for individual examiners: comparison of no defect with small defects

Examiner	Radiograph	Cone beam	P-value
1	0.833	1.000	0.114
2	0.917	1.000	0.317
3	0.667	1.000	0.002
4	0.722	1.000	0.055
5	0.750	1.000	0.025
6	0.764	1.000	0.071
Mean (SD)	0.766 (0.088)	1.000 (0.000)	0.028*

SD, standard deviation; ROC, Receiver Operator Characteristic; CBCT, cone beam computed tomography.

*P-value from Wilcoxon matched-pairs, signed-ranks test.

Table 6 Area under the curve from ROC analysis of radiograph and CBCT for individual examiners: comparison of no defect with large defects

Examiner	Radiograph	Cone beam	P-value
1	0.917	1.000	0.317
2	0.917	1.000	0.317
3	0.750	1.000	0.025
4	0.806	1.000	0.112
5	0.667	1.000	0.002
6	0.778	1.000	0.082
Mean (SD)	0.860 (0.098)	1.000 (0.000)	0.027*

SD, standard deviation; ROC, Receiver Operator Characteristic; CBCT, cone beam computed tomography.

*P-value from Wilcoxon matched-pairs, signed-ranks test.

identified all periapical lesions in 24.8% and 100% of cases, respectively. Both imaging techniques had high specificity values of 1.000, i.e. both techniques were equally accurate in diagnosing healthy periapical periodontium (Tables 1–3). The sensitivity of intraoral radiography was lower than CBCT for detecting the presence of both ‘small’ periapical lesions (0.200; $P = 0.014$) and ‘large’ periapical lesions (0.350; $P = 0.024$).

Table 7 Kappa values for intra- and inter-examiner agreement in reading radiographs and CBCT images

Examiner	Intra-examiner kappa	
	Radiograph	Cone beam
1	0.386	0.670
2	0.294	1.000
3	0.182	0.686
4	0.667	0.531
5	1.000	ND
6	0.526	ND
Mean (SD)	0.509 (0.295)	0.722 (0.198)
Inter-examiner kappa	0.351	0.641

SD, standard deviation; ND, not done.

The ROC analysis for intraoral radiography revealed a lower Az value (0.766) than CBCT (1.000) for the detection of smaller periapical lesions ($P = 0.028$). Similarly, the intraoral radiography Az value (0.860) for the detection of larger periapical lesions was also less than that for CBCT (1.000) ($P = 0.027$). The overall Az value regardless of size of lesion was 0.791 for intraoral radiography and 1.000 for CBCT ($P = 0.027$) (Tables 4–6).

The kappa value for overall inter-examiner agreement was 0.351 and 0.641 for intraoral radiography and CBCT, respectively. The mean intra-examiner agreement was 0.509 and 0.722 for intraoral radiography and CBCT, respectively (Table 7).

Discussion

A diagnostic test should exhibit validity and reliability if it is to be useful (Zakariassen *et al.* 1984). In this study, the diagnostic tests under investigation (intraoral radiographs and CBCT) should be able to detect periapical disease when it is present (validity) and should be repeatable, i.e. generate the same result (reliability).

Periapical lesions were created immediately below the distal root of first molar tooth as it was surrounded by more cancellous bone than its mesial counterpart, this also perhaps explains why periapical radiolucent lesions are usually first detected on the mesial root(s) of mandibular first molars (Bender 1982). The distal root was also easier to extract without damaging it as it tended to be straighter than the mesial root. This investigation compared the efficacy of intraoral radiography and CBCT in detecting artificial periapical lesions limited to the cancellous bone in human mandibles. The results of this study suggest that CBCT imaging of teeth with endodontic problems (e.g. pulpitis

and periapical periodontitis) lesions is of value. This study showed that intraoral radiography was not sensitive at detecting periapical lesions of either size; the overall sensitivity was 0.248 (24.8%). However, the intraoral radiography was more accurate at diagnosing 'large' periapical lesions than 'small' periapical lesions. This probably reflects the increased volume of bone destruction, and is in agreement with the findings of Paurazas *et al.* (2000). Intraoral radiography was accurate in confirming when periapical lesions were not present, in this situation there was 100% accuracy (specificity 1.0). CBCT was 100% accurate in diagnosing the presence (sensitivity 1.0) and absence (specificity 1.0) of periapical lesions. ROC analysis confirmed that CBCT was significantly more accurate than intraoral radiography in detecting the presence of periapical disease. The overall diagnostic accuracy of intraoral radiographs (ROC Az value 0.791) in this study was in the same order of magnitude as other studies assessing artificial periapical lesions within the cancellous bone using digital (CCD) intraoral radiography (Kullendorff *et al.* 1996, Paurazas *et al.* 2000). The results of the sensitivity, specificity, PPV, NPV and ROC analysis of intraoral radiographs in the present study are also similar to the findings of a recent clinical study (Estrela *et al.* 2008). In the clinical setting, the detection of periapical lesions may have been even poorer with intraoral radiography because of the additional problem of less than ideal irradiation geometry associated with the difficulty in placing image receptors in an ideal position in certain regions of the oral cavity. In addition, divergent roots may also be displayed with varying degrees of distortion on radiographs (Lofthag-Hansen *et al.* 2007).

It would have been desirable to use human cadavers to accurately reproduce soft tissue attenuation and scatter from the CBCT X-ray beam. However, as this study was being carried out in an unlicensed area (private practice) rather than a University Institution, this was not possible because of Government legislation (Human Tissue Act 2004). Therefore, dry mandibles rehydrated in soapy water were used. Prosthetic dental wax was used as a soft tissue substitute as it has the same optical density as human soft tissue (Ricketts *et al.* 1995, 1997). Pilot studies confirmed that the radiographic and CBCT appearance of this mandible model closely replicated clinical images on patients.

The results of this study appear to validate clinical studies that have used CBCT as the 'gold standard' for determining the presence or absence of periapical lesions (Lofthag-Hansen *et al.* 2007, Estrela *et al.*

2008, Low *et al.* 2008). CBCT has evolved from CT. Essentially, the collected raw data from both imaging techniques may be formatted and viewed in similar ways. Velvart *et al.* (2001) compared the diagnostic information of CT scans with periapical radiographs of 50 mandibular posterior teeth scheduled for periapical surgery to the clinical findings at the time of surgery. They found that CT was 100% accurate in detecting the presence of periapical lesions compared with 78% for intraoral radiographs. The higher detection rate of periapical lesions with radiographs in this study may have been due to long-standing chronic periapical periodontitis, which may have eroded the cortical bone. It would have been interesting to correlate the cortical plate involvement as seen on coronal CT slices to the corresponding radiographs. Similar results were also found by Huuonen *et al.* (2006) when they assessed maxillary molar teeth. The reduced accuracy of intraoral radiography in detecting periapical lesions using intraoral radiography compared with CT or CBCT technology in these clinical studies and the present study may be due to the fact that the lesions were confined to the cancellous bone only. This results in the mineral bone loss of the periapical lesion being masked by the denser, more mineralized cortical plate, which means that these lesions are more difficult to detect with intraoral radiographs (Schwartz & Foster 1971, Bender 1982). Changes in bone density, trabeculae architecture, bone marrow spaces and morphological variations in the apical region would also be missed (Halse *et al.* 2002).

Cone beam computed tomography software allows the clinician to view reconstructed slices of data without the overlying cortical plate (anatomical noise), which may otherwise hide what is actually occurring within the cancellous bone. With CBCT, the examiner usually specifies the orientation of the reconstructed slice(s) resulting in orthogonal views that are parallel and perpendicular to the long axis of the root under investigation. In addition, the thickness of each slice (i.e. how much information) and the interval between each slice can be adjusted. These factors ultimately result in periapical lesions being significantly more perceptible to the examiner compared with intraoral radiographs as the CBCT software may be used to maximize the diagnostic yield of the captured data in each case. In addition, the reconstructed slices are geometrically accurate. Therefore, periapical lesions will not change size or disappear on reconstructed scans as can happen with intraoral radiography as a result of poor irradiation geometry (Gröndahl & Huuonen

2004). Not only can the presence of a periapical lesion(s) be diagnosed with CBCT, but the specific root that it is associated with can also be confirmed. This may influence treatment planning (Lofthag-Hansen *et al.* 2007). It was interesting to note that the favourable results achieved with CBCT in this study were despite the fact that none of the examiners had previous experience in the interpretation of CBCT data.

A digital intraoral radiographic system rather than a conventional X-ray film was used in this study as the resulting image was dynamic and therefore could be easily enhanced (contrast/brightness) to improve the diagnostic yield of the radiographic image (Kullendorff & Nilsson 1996). Several studies have shown that there is no difference in the detectability of artificially created periapical lesions using conventional X-ray films and digital sensors (Kullendorff & Nilsson 1996, Barbat & Messer 1998, Stavropoulos & Wenzel 2007). Enhancing the radiographic images (e.g. colourizing and inverting) with software was not carried out as it has not been shown to enhance the detection of periapical lesions (Barbat & Messer 1998). The detection rate of periapical lesions with radiographs may have been higher if parallax radiographs were taken of each tooth (Brynolf 1970a,b) and if a consensus agreement between all the examiners was reached for each case (Molven *et al.* 2002).

There is a school of thought that believes that periapical lesions confined to the cancellous bone and not affecting the cortical plate cannot be detected using intraoral radiography (Bender & Seltzer 1961, Radaman & Mitchell 1962, Schwartz & Foster 1971, Bender 1982). However, in the present study a number of periapical lesions confined to cancellous bone were detected using intraoral radiography. Similar findings have been reported by other investigators (Barbat & Messer 1998, Marmary *et al.* 1999, Paurazas *et al.* 2000, Wallace *et al.* 2001).

The inter- and intra-examiner agreement between the examiners was higher with CBCT, suggesting that CBCT scans are perhaps easier to interpret compared with periapical radiographs. Goldman *et al.* (1972, 1974) found inter-examiner agreement between their six examiners was 47% and intra-examiner agreement was between 74% and 80% using intraoral radiographs. Similar results were presented by Zakariasen *et al.* (1984), who reported that inter-examiner agreement was only 38% and intra-observer agreement was between 64.5 and 81%. Although not directly comparable with the Kappa results in this study, they do seem to suggest a similar level of agreement.

The results of this study provides evidence of CBCT's validity and reliability for detecting the presence of periapical lesions. Further investigations are required to determine the diagnostic validity of different CBCT scanners and the effect of changing the exposure parameters on the detection of periapical lesions. Intraoral radiography, which is the imaging technique of choice for the management for periapical disease, appears to be quite crude on both accounts (validity and reliability) in the detection of the presence of periapical lesions. The superior accuracy of CBCT may result in a review of the radiographic techniques used in the management of endodontic problems, and to detect periapical lesions in outcome and epidemiological studies since the prevalence of apical disease may be significantly under-estimated with conventional radiography (Estrela *et al.* 2008, Patel *et al.* 2009).

Radiation exposure to patients should be kept as low as reasonably practicable (ALARP). The effective radiation dose from CBCT is higher than conventional radiography, therefore when considering taking a CBCT scan the benefits of this investigation must outweigh any potential risks to the patient (Farman & Farman 2005). Evidence-based selection criteria for the use of CBCT are required (Patel *et al.* 2007, Patel 2009).

Conclusion

External factors (i.e. anatomical noise and poor irradiation geometry), which are not in the operators control with intraoral radiography, dictate what might or might not be revealed on a conventional periapical image. CBCT eliminates these external factors. In addition, it allows the clinician to select the most relevant views. This study indicates that this results in improved detection of the presence and absence of periapical disease.

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The detection and management of root resorption lesions using intraoral radiography and cone beam computed tomography – an *in vivo* investigation

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Abstract

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The detection and management of root resorption lesions using intraoral radiography and cone beam computed tomography – an *in vivo* investigation. *International Endodontic Journal*, 42, 831–838, 2009.

Aim To compare the accuracy of intraoral periapical radiography with cone beam computed tomography (CBCT) for the detection and management of resorption lesions.

Methodology Digital intraoral radiographs and CBCT scans were taken of patients with internal resorption ($n = 5$), external cervical resorption ($n = 5$) and no resorption (controls) ($n = 5$). A 'reference standard' diagnosis and treatment plan was devised for each tooth. Sensitivity, specificity, positive predictive values, negative predictive values and receiver operator characteristic (ROC) curves, as well as the reproducibility of each technique were determined for diagnostic accuracy and treatment option chosen.

Results The intraoral radiography ROC Az values were 0.780 and 0.830 for diagnostic accuracy of internal and external cervical resorption respectively. The CBCT ROC Az values were 1.000 for both internal and external cervical resorption. There was a significantly higher prevalence ($P = 0.028$) for the correct treatment option being chosen with CBCT (%) compared with intraoral radiographs (%).

Conclusion CBCT was effective and reliable in detecting the presence of resorption lesions. Although digital intraoral radiography resulted in an acceptable level of accuracy, the superior accuracy of CBCT may result in a review of the radiographic techniques used for assessing the type of resorption lesion present. CBCT's superior diagnostic accuracy also resulted in an increased likelihood of correct management of resorption lesions.

Keywords: cone beam computed tomography, external cervical resorption, internal resorption.

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Introduction

Root resorption is the loss of hard dental tissue (i.e. cementum and dentine) as a result of odontoclastic cell action. Root resorption is inhibited by the protective unmineralized innermost pre-dentine and outermost pre-cementum surfaces of the root (Lindskog *et al.* 1983, Wedenberg & Lindskog 1985, Heithersay 2004). The resorptive process may be inconsequential, lasting

for 2–3 weeks only (Fuss *et al.* 2003). However, with continual stimulation by infection (Gunraj 1999, Tronstad 2002), or pressure (Fuss *et al.* 2003) the odontoclasts will continue to resorb the damaged surface of the root which may result in extensive damage to the tooth.

Resorption defects can be challenging to diagnose correctly which may result in inappropriate treatment being carried out (Chapnick 1989, Patel & Pitt Ford 2007, Patel & Dawood 2007). An accurate diagnosis is essential for an appropriate treatment plan to be devised. Radiographically, internal root resorption appears as a 'ballooning-out' of the root canal. The

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resorption lesion is radiolucent and has smooth, well defined margins and is oval or round in shape (Çalışkan & Türkün 1997, Whitworth 2004). The radiographic appearance of external cervical root resorption depends on the severity of the lesion. Early lesions appear as cloudy radiolucencies in the cervical region of the tooth and the border of the defect is usually poorly defined. The root canal walls should be visible and running vertically through the radiolucent defect, indicating that the lesion lies on the external surface of the root (Heithersay 1999, Tronstad 2002, Heithersay 2004). Root resorption may be confirmed using the parallax radiograph technique (Haapasalo & Endal 2006, Patel & Dawood 2007). The parallax technique may be helpful to detect and determine the location (palatal or labial) of the external cervical root resorption lesions. However, intraoral radiographs do not provide an indication of the true dimensions of such lesions (Kim *et al.* 2003). The resorption defect may spread within the root in all directions, this may not be reflected in the size and position of the radiolucency detected on the radiograph (Patel & Dawood 2007).

One of the major problems with diagnosing and predictably managing internal and external cervical root resorption is that intraoral radiographs only reveal limited diagnostic information (Cohenca *et al.* 2007). The amount of information gained from these analogue and digital periapical radiographs is incomplete due to the fact that the three-dimensional anatomy of the area being radiographed is compressed into a two-dimensional image or shadowgraph (Patel *et al.* 2009). In addition, anatomical noise may result in an underestimation of the actual size of the resorption lesion.

Cone beam computed tomography (CBCT) technology has been specifically designed to produce three-dimensional scans of the maxillo-facial skeleton (Mozzo *et al.* 1999, Arai *et al.* 1999). One of CBCT's major advantages over computed tomography (CT) scanners is the reduction in radiation exposure (Cotton *et al.* 2007, Patel *et al.* 2007, Scarfe & Farman 2008). CBCT has been successfully used to evaluate the true nature and severity of resorption lesions in isolated case reports (Cohenca *et al.* 2007, Patel & Dawood 2007) indicating that the clinician could confidently diagnose and manage the defect.

There are no studies which have tested the ability of CBCT to improve the diagnosis of internal and external cervical root resorption. The aim of the present study was firstly to compare the diagnostic accuracy of intraoral periapical radiography with CBCT for the detection of internal and external

cervical resorption, and secondly to compare the treatment strategies chosen for the management of resorption lesions using intraoral periapical radiography and CBCT.

Materials and methods

Data collection

The radiographs and CBCT data records of 15 teeth (from 15 patients) were included. The teeth had either been successfully managed by one operator in specialist practice ($n = 12$) or by endodontic postgraduate students ($n = 3$) under the supervision of the same individual. Ethical approval was granted to use the clinical data for research purposes. The study population consisted of 10 males and five females:

- Five teeth were diagnosed with internal resorption.
- Five teeth were diagnosed with external cervical resorption.
- Five teeth were controls (i.e. no resorption present).

The radiographs and CBCT data were assessed by a consensus committee consisting of three experienced specialist endodontists who confirmed the diagnosis and ideal treatment plan for each case. The three members of this consensus committee between them had 60 years experience in Endodontology. All three members of the consensus committee independently assessed the resorption cases. There was unanimous agreement between the consensus committee. Their diagnoses were confirmed in all cases when the resorption lesions were treated, in all cases the diagnoses of the consensus committee were correct.

Radiographic technique

Patients were radiographed with a dental X-ray machine (Planmeca Prostyle Intra, Helsinki, Finland) using a digital CCD sensor (Schick Technologies, New York, NY, USA) with exposure parameters of 66 kV, 7.5 mA and a 0.10 s and a paralleling technique. CBCT scans were either taken using a small volume CBCT scanner (3D Accuitomo 80; J Morita Manufacturing, Kyoto, Japan) with exposure parameters 80 kV, 3.0 mA and 17.5 s or a large volume scanner (i-CAT, Imaging Sciences International, Hatfield, PA, USA) with exposure parameters of 120 Kv, 5 mA and 20 s for the large volume CBCT scan.

CBCT data were reformatted to align the root axis with the vertical plane in the sagittal and coronal views. The brightness and contrast of all the acquired images

was enhanced to improve visualization of the resorption lesions. All CBCT data were reformatted (0.125 mm slice intervals and 1.5 mm slice thicknesses).

Radiological assessment

Six examiners (two specialist endodontists and four endodontic post-graduates) individually assessed the radiographs and CBCT scans in the following sequence: session 1 – radiographs, session 2 – CBCT scans, session 3 – radiographs and CBCT scans repeated (to assess intra-observer agreement).

All the examiners were reminded of the salient features of resorption lesions using sample radiographs and CBCT images. The examiners were then trained using radiographs and CBCT images of teeth with and without internal and external cervical root resorption. Only examiners who were able to correctly diagnose images in at least 80% of the cases were allowed to go on to assess the test cases. After the completion of this training session the examiners were shown the ‘training’ cases again with a member of the consensus committee who discussed the salient diagnostic features in each case. This served to consolidate the knowledge of the radiographic features of resorption lesions. These discussion sessions with the consensus committee member were carried out over three sessions, with two examiners in each session.

The test images were randomly ordered in each session and viewed as a powerpoint presentation (Microsoft Corp, Washington, WA, USA) on a laptop computer (Toshiba Portege R500-11Z; Tokyo, Japan) which had a Liquid Crystal Display (LCD) screen with a pixel resolution of 1280 × 1024. A CBCT image that best confirmed the presence or absence of the resorp-

tion defect in the sagittal and coronal planes was used as the starting point for each tooth observation. Examiners also had access to the raw CBCT data allowing them to scroll through any of the orthogonal scans. All images were assessed in a dark room.

Examiners were asked to note down the presence or absence of internal resorption and external cervical root resorption and their treatment plan (Table 1 & Fig. 1). In each case there was only one correct diagnosis and treatment option that had been previously established by the consensus committee and in resorption cases confirmed after the completion of the treatment of the lesion.

There was at least a 1 week interval between each session. Eight radiographs and eight CBCT scans were randomly chosen and assessed in session 3 to assess intra-examiner agreement.

Data analysis

Stata™ software (Stata 9, College Station, TX, USA) were used to analyse the raw data. Sensitivity, specificity and predictive values were determined; receiver operating characteristic (ROC) curve analysis was used to assess the diagnostic accuracy of each examiner and each imaging system in detecting the presence of each type of resorption defect against the alternate type of defect and controls. Summary data were described using mean (standard deviation) and median (inter-quartile range) to accommodate the small sample size, and differences between radiographs and CBCT were analysed using Wilcoxon matched-pairs, signed-ranks test. Inter-examiner and intra-examiner agreement was assessed by Kappa statistics for scores from both the intraoral radiographs and CBCT scans.

Table 1 Questionnaire which examiners completed for each case

	Definitely present	Probably present	Unsure	Probably not present	Definitely not present
Internal resorption					
External cervical resorption					
	Very sure	Reasonably sure	Unsure	Reasonably unsure	Very unsure
• Leave alone					
• Review					
• Nonsurgical endodontic treatment					
• Surgical endodontic treatment					
• Combination of nonsurgical and surgical endodontic treatment					
• Extraction					

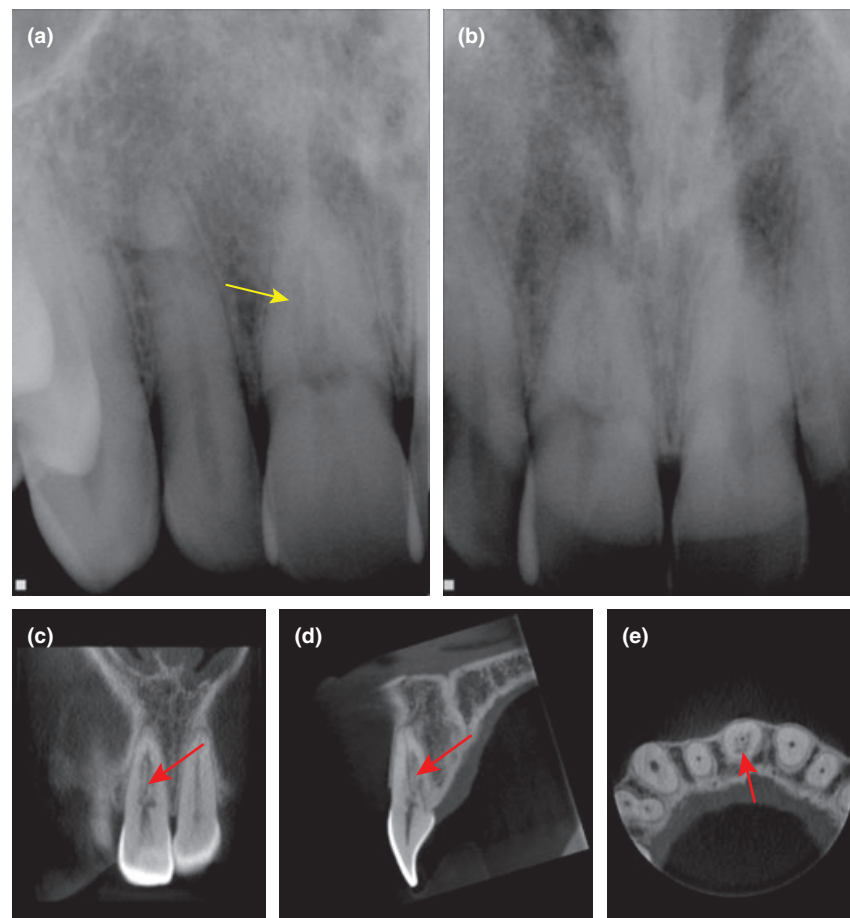


Figure 1 (a–b) Typical radiographs shown in session 1 and 3 to assess diagnostic accuracy of intraoral radiographs. A cloudy radiolucency (yellow arrow) is present in the mid-third of the root. (c–e) A typical series of CBCT reconstructed (coronal, sagittal and axial) views of the same tooth shown in session 2 and 3 to assess diagnostic accuracy of cone beam computed tomography. An external cervical root resorption lesion (red arrow) can clearly be seen, note the severity of the lesion.

Results

Diagnosis

The overall sensitivity of intraoral radiography was lower than CBCT (Table 2). The ROC analysis revealed that intraoral radiography had a lower median Az value (0.780) than CBCT (1.000) for diagnosing internal resorption ($P = 0.027$). Similarly, the mean Az value (0.830) of intraoral radiography was lower than CBCT (1.000) for diagnosing external cervical resorption ($P = 0.027$) (Tables 3–4).

The kappa value for inter-examiner agreement was 0.365 and 0.925 for intraoral radiography and CBCT respectively for the diagnosis of internal resorption. The kappa value for inter-examiner agreement was 0.444

and 0.951 for intraoral radiography and CBCT respectively for the diagnosis of external cervical resorption.

Intra-examiner agreement was assessed in 53% (eight of the 15) of the cases for each imaging system in session 3. The median intra-examiner agreement was 0.810 and 0.885 for intraoral radiography and CBCT respectively for the diagnosis of internal resorption. The mean intra-examiner agreement was 0.657 and 1.000 for intraoral radiographs and CBCT respectively for the diagnosis of external cervical resorption (Table 5).

Treatment options

The median percentage correct treatment option selected by the six examiners was 53% and 73% for

Table 2 Mean (standard deviation), median [inter-quartile range] of sensitivity, specificity, PPV and NPV for radiographs and CBCT for detecting (a) internal and (b) external resorption at confidence level 5

	Sensitivity	Specificity	PPV	NPV
a				
Radiographs	0.590 (0.216)	0.974 (0.064)	0.945 (0.136)	0.713 (0.120)
	0.51 [0.46–0.86]	1.00 [1.00–1.00]	1.00 [1.00–1.00]	0.70 [0.61–0.83]
CBCT	1.000 (0.000)	1.000 (0.000)	1.000 (0.000)	1.000 (0.000)
	1.00 [1.00–1.00]	1.00 [1.00–1.00]	1.00 [1.00–1.00]	1.00 [1.00–1.00]
b				
Radiographs	0.724 (0.302)	0.790 (0.076)	0.645 (0.114)	0.865 (0.157)
	0.82 [0.36–1.00]	0.79 [0.78–0.81]	0.64 [0.57–0.67]	0.93 [0.67–1.00]
CBCT	1.000 (0.000)	1.000 (0.000)	1.000 (0.000)	1.000 (0.000)
	1.00 [1.00–1.00]	1.00 [1.00–1.00]	1.00 [1.00–1.00]	1.00 [1.00–1.00]

PPV, positive predictive value; NPV, negative predictive value.

Table 3 Mean (standard deviation), median [inter-quartile range] of area under the curve from ROC analysis of radiographs and CBCT for individual examiners: correct diagnosis of internal resorption at confidence level 5

Examiner	Radiograph	Cone beam	P-value
1	0.800	1.000	0.103
2	0.840	1.000	0.249
3	0.800	1.000	0.103
4	0.720	1.000	0.053
5	0.760	1.000	0.073
6	0.760	1.000	0.073
Mean (SD)	0.780 (0.078)	1.000 (0.000)	
Median [IQR]	0.780 [0.760–0.800]	1.000 [1.000–1.000]	0.027 ^a

^aWilcoxon matched-pairs, signed-ranks test for differences in sensitivity.**Table 4** Mean (standard deviation), median [inter-quartile range] of area under the curve from ROC analysis of radiographs and CBCT for individual examiners: correct diagnosis of external resorption at confidence level 5

Examiner	Radiograph	Cone beam	P-value
1	0.900	1.000	0.134
2	0.880	1.000	0.179
3	0.900	1.000	0.134
4	0.740	1.000	0.051
5	0.760	1.000	0.023
6	0.820	1.000	0.062
Mean (SD)	0.830 (0.070)	1.000 (0.000)	
Median [IQR]	0.850 [0.760–0.900]	1.000 [1.000–1.000]	0.027 ^a

^aWilcoxon matched-pairs, signed-ranks test for differences in sensitivity.**Table 5** Kappa values for inter-examiner agreement and mean (standard deviation), median [inter-quartile range] of Kappa values for intra-examiner agreement in reading radiograph and CBCT for internal and external resorption

	Internal resorption		External resorption	
	Radiograph	Cone beam	Radiograph	Cone beam
Inter-examiner	0.365	0.925	0.444	0.951
Intra-examiner	0.711 (0.378)	0.788 (0.257)	0.625 (0.288)	0.966 (0.084)
	0.810 [0.600–1.000]	0.885 [0.529–1.000]	0.657 [0.556–0.750]	1.000 [1.000–1.000]

Table 6 Mean (standard deviation), median [inter-quartile range] of percentage correct treatment decisions chosen by the examiners with radiographs and CBCT at confidence levels (5) and (4 + 5)

	Confidence level (5)		Confidence level (4 + 5)	
	Radiographs	CBCT	Radiographs	CBCT
Mean (SD)	52 (15)	74 (9)	60 (10)	79 (8)
Median [IQR]	53 [47–67]	73 [73–80]	60 [53–67]	80 [73–87]

Table 7 Mean (standard deviation), median [inter-quartile range] of Kappa values for agreement in treatment decisions between sessions for radiographs and CBCT

	Radiograph	CBCT
Mean (SD)	0.606 (0.274)	0.632 (0.360)
Median [IQR]	0.629 [0.400–0.750]	0.686 [0.250–1.000]

intraoral radiography and CBCT respectively when assessed using the confidence level of 5 alone (Table 6). These results increased to a median of 60% and 80% for intraoral radiographs and CBCT respectively when assessed accepting a combination of confidence levels 4 and 5. This difference was statistically significant ($P = 0.028$).

There was poor agreement between radiography and cone beam decisions (median kappa = 0.127). The median kappa for intra-examiner agreement was 0.629 and 0.686 for intraoral radiographs and CBCT respectively (Table 7).

Discussion

Ideally a diagnostic test for root resorption should be able to correctly detect the presence or absence of different types of root resorption (validity), and should be repeatable, i.e. to generate the same result (reliability). In this study intraoral radiographs and CBCT were assessed for their diagnostic accuracy, and their ability to allow the examiner to arrive at the correct treatment option. This is the first clinical study that has attempted to validate CBCT for the clinical management of internal and external cervical root resorption.

The test sample size included 10 teeth with either internal or external cervical root resorption defects. This small sample size reflects the rare occurrence of these type of defects (Haapasalo & Endal 2006), and was in fact reached after collecting cases in a specialist practice and in a teaching hospital for almost 2 years. Five additional healthy teeth were included as controls. The results of this study suggest that CBCT imaging of teeth with internal and external cervical root resorption is of value. Although intraoral radiography was reasonably accurate in correctly diagnosing internal and external cervical root resorption, CBCT scans resulted in perfect diagnosis of the presence and type of root resorption. This is also reflected in the sensitivity and specificity results. Intraoral radiography was slightly more accurate in diagnosing external cervical root resorption than internal root resorption. The slightly more accurate diagnosis of external cervical root resorption with intraoral radiographs may be due to the fact that their irregular margins may be pathognomic of this type of resorption lesion. The examiner's ability to choose the correct treatment option was also improved when CBCT was used. Despite perfect diagnostic accuracy, the treatment decisions with CBCT were only 80% correct when compared with the consensus committee.

Metz (1989) has suggested that a ROC Az value between 0.75–0.80 is acceptable for clinical imaging techniques. The overall diagnostic accuracy of intraoral radiographs for detecting internal (ROC Az value 0.780) and external cervical resorption (ROC Az value 0.830) confirmed that intraoral radiography is a fairly accurate diagnostic tool. The results from the present study were in the same order of magnitude as previous

studies assessing artificially prepared root resorption lesions assessed using ROC analysis (Borg *et al.* 1998, Holmes *et al.* 2001). The perfect diagnostic accuracy of CBCT in diagnosing resorption lesions is a result of the three-dimensional assessment of these resorption lesions. The sophisticated CBCT software allows the clinician to select the most favourable orthogonal views for each specific problem being assessed. In addition the thickness of each slice (i.e. how much information) and the interval between each slice may be adjusted. These factors ultimately result in root resorption lesions being significantly more perceptible to the clinician compared with intraoral radiographs. Unlike other studies (Borg *et al.* 1998, Kamburoğlu *et al.* 2008a,b) assessing root resorption, a third session was included in our study to assess intra-examiner agreement. There was at least a 1 week interval between each viewing session to reduce the likelihood of the examiner recalling any of the previous cases they had assessed. Images were viewed as a powerpoint presentation in order to facilitate the examiners' work.

The examiner's results were compared to the 'reference standard' results of the consensus committee. The question arises as to how valid were the diagnosis and treatment plan for each resorption lesion assessed by the consensus committee. Ideally the 'reference standard' test would be to extract all these teeth to confirm whether the results from assessing the radiographs and CBCT scans correlate to macroscopic and histological findings of the extracted teeth. Obviously, this is not possible in healthy teeth and/or teeth which can be treated successfully. However, in the treatment phase the accuracy of the diagnosis agreed by the consensus panel was confirmed in all cases. Of the 10 resorption cases, six were deemed to be successful at 1 year follow up which would suggest that the consensus panel were correct with their treatment options. Two of the remaining four teeth that were unsalvageable were extracted. The last two patients did not attend the recall visit.

The results of this study validate the use of CBCT to determine the presence and type of root resorption. CBCT also appears to be extremely useful for assessing the severity of resorption lesions, which in turn influences the treatment decision made (Cohenca *et al.* 2007). It would be desirable, in a future study to compare intraoral radiographs with CBCT for assessing the location of the resorption lesions as this factor may influence its management.

Each case in this study was unique, therefore the severity and location of the resorption lesions varied from case to case. In addition anatomical noise and

geometrical positioning of the film holder may also have contributed to the poorer diagnostic accuracy of intraoral radiography. However, it was important to carry out a clinical study as mechanically 'machined' resorption lesions used in *ex-vivo* studies, although standardized, do not truly reflect the true nature of resorption lesions, as *in vivo* resorption lesions are not perfect semi-spherical shaped cavities.

It was interesting to note that the favourable results achieved with CBCT in this study were despite the fact that none of the examiners had previous experience in the interpretation of CBCT data. In addition there was no difference in the results between the examiners with different levels of experience (i.e. endodontists versus post-graduate students). The poorer results achieved with intraoral radiographs confirmed the difficulty using these two-dimensional images for correctly diagnosing root resorption.

With a digital intraoral radiographic system the resulting image is dynamic allowing it to be easily enhanced (contrast/brightness) to improve the diagnostic yield of the radiographic image (Kullendorf & Nilsson 1996). Several studies have concluded that intraoral radiographic films and CCD digital sensors perform equally well in diagnosing resorptive lesions (Borg *et al.* 1998, Kamburoğlu *et al.* 2008a,b). The examiners were allowed to adjust the contrast and brightness of the radiographic images. However, they did not have access to any other image enhancement software (for example, colourizing, revealing and inverting) as this type of image manipulation had been shown not be useful in other aspects of endodontic diagnosis (Kullendorf *et al.* 1996, Barbat & Messer 1998, Kamburoğlu *et al.* 2008b). In our study a LCD screen with a high pixel resolution was chosen to provide an high image quality of the radiographs and CBCT scans. There is evidence to suggest that LCD and high resolution cathode ray tubes are equally effective for assessing CBCT and digital radiographs (Baksi *et al.* 2009). A consensus agreement between all the examiners may also have improved the results from the radiographs used in the study (Molven *et al.* 2002). This was not done in the present study as it does not represent the normal clinical situation for most practitioners.

Only potential examiners who were shown to be competent in a pilot study were accepted as examiners. Intra-examiner agreement was assessed by having a third examiner session, with a selection of randomly selected intraoral radiographs and CBCT scans, rather than two individual sessions to assess intraoral radio-

graphs and CBCT scans respectively. The rationale for this was that the majority of examiners were happier to commit to three rather than four sessions. The number of cases selected for the third session was kept to 16 to prevent examiner fatigue.

The inter-examiner and intra-examiner agreement between the examiners was higher with CBCT. This is a result of the examiner being able to select with CBCT reconstructed images with no overlying anatomical noise and having the ability to assess the resorption lesion in any dimension (for example, reconstructed axial slices). Similar results have been found in studies comparing the diagnostic accuracy of intraoral radiographs with CBCT for assessing periapical lesions (Patel *et al.* 2009, Özen *et al.* 2009). Zachariassen *et al.* (1984) also found a poor inter-examiner agreement with intraoral radiographs.

Conclusion

The results of this study indicate CBCT's validity and reliability for detecting the presence of resorption lesions. Although intraoral radiography resulted in an above average level of accuracy, the superior accuracy of CBCT may result in a review of the radiographic techniques used for assessing the presence or type of resorption lesions. CBCT's superior diagnostic accuracy also resulted in an increased likelihood of correct management of resorption lesions compared with intraoral radiographs.

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The detection of periapical pathosis using periapical radiography and cone beam computed tomography – Part 1: pre-operative status

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Abstract

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Aim Part 1 of this 2 part study aims to compare the prevalence of periapical lesions on individual roots viewed with intraoral (periapical) radiographs and cone-beam computed tomography (CBCT) of teeth treatment planned for endodontic treatment.[§]

Methodology Diagnostic periapical radiographs and CBCT scans were taken of 151 teeth in 132 patients diagnosed with primary endodontic disease. The presence or absence of periapical lesions was assessed by a consensus panel consisting of two calibrated examiners, a consensus agreement was reached if there was any disagreement. The panel viewed the images under standardised conditions. Part 2 will compare the radiographic outcome 1 year after completion of primary root canal treatment.[¶]

Results Two hundred and seventy-three paired roots were assessed with both radiological systems, periapical lesions were present in 55 (20%) and absent in 218 (80%) roots assessed with periapical radiographs. When the same 273 sets of roots were assessed with CBCT, lesions were present in 130 (48%) and absent in 143 (52%) roots. Seventy-five additional roots were detected with CBCT.

Conclusion The limitations of periapical radiographs which may hinder the detection of periapical lesions are overcome with CBCT. This results in firstly, more roots being assessed, and secondly, more periapical lesions being detected with CBCT.

Keywords: cone beam computed tomography, intra-oral radiographs, periapical lesions.

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§[Correction added after online publication, 25th May 2012: Aim changed to refer to study being in two parts.]

¶[Correction added after online publication, 25th May 2012: 'intraoral' changed to 'periapical radiographs' and sentence added to explain methodology of second part of study.]

Introduction

Radiographic assessment is an essential component in the diagnosis of teeth with suspected endodontic problems (Patel *et al.* 2009a, Özen *et al.* 2009, Yoshioka *et al.* 2011). The specific view of choice for endodontic assessment is a periapical (intraoral) radiograph using a beam aiming device to ensure a minimally distorted and reproducible image (Jorge *et al.* 2008, Patel *et al.* 2009a).

Ideally, the radiographic image will confirm the number of root canals, their configuration together with the

presence or absence of periapical lesions and their location (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008, Neelakantan *et al.* 2010). This important information not only helps to confirm the diagnosis, but also aids treatment planning and management and is a baseline for assessing the outcome of each unique endodontic problem.

It is well established that radiographs have limitations; these include anatomical noise, the two dimensionality and geometric distortion (Huomonen & Ørstavik 2002, Patel *et al.* 2009a). The ideal imaging technique should set the clinician free from the constraints of these limitations.

Cone-beam computed tomography (CBCT) may be used to overcome these limitations. CBCT has been specifically designed to produce three-dimensional images of the maxillofacial skeleton. With CBCT, the entire 'region of interest' is scanned in a single rotation of the X-ray source and reciprocal detector around the patient's head. For endodontic purposes, the limited volume or focused CBCT scanners capture small volumes of data encompassing just 3–4 individual teeth. For example, the 3D Accutomo (J Morita, Osaka, Japan) can capture a 40-mm³ volume of data, which is similar in overall height and width to a periapical radiograph. The major advantage of limited (small field of view) CBCT scanners over medical-grade computer tomography is the relatively low-effective radiation dose the patient is exposed to (Loubele *et al.* 2009). Software generates reconstructed images in three orthogonal planes within minutes. Reconstructed images of data without the overlying cortical plate (anatomical noise) that may otherwise hide what is actually occurring within the cancellous bone may therefore be assessed. The clinician can also orient the reconstructed slice(s) resulting in orthogonal views that are parallel and perpendicular to the long axis of the root under investigation. These factors ultimately result in the number of roots, canals and periapical lesions present in the tooth being significantly more perceptible to the clinician compared with periapical radiographs (Matherne *et al.* 2008, Paula-Silva *et al.* 2009a, Blattner *et al.* 2010). Not only can the presence of a periapical lesion be diagnosed with CBCT, but the specific root that it is associated with can also be confirmed (Rigolone *et al.* 2003, Gröndahl & Huomonen 2004).

Laboratory studies have confirmed that CBCT improves the detection of presence or absence of periapical lesions when compared with periapical radiographs (Stavropoulos & Wenzel 2007, Özen *et al.* 2009, Patel *et al.* 2009b). Clinical studies have compared periapical radiographs and CBCT scans for detecting periapical

periodontitis; however, these studies have generally focused on the prevalence of periapical lesions in teeth with failing root canal treatment (Lofthag-Hansen *et al.* 2007, Estrela *et al.* 2008, Low *et al.* 2008, Bornstein *et al.* 2011). There is a paucity of literature comparing periapical radiographs and CBCT scans for detecting periapical periodontitis in untreated teeth diagnosed with endodontic disease.

This clinical study has two purposes: firstly, to compare the prevalence of periapical lesions on individual roots of teeth viewed with periapical radiographs and CBCT of teeth treatment planned for primary root canal treatment, which is described below. The second part of this clinical study was to determine the radiological outcome one year after completion of primary root canal treatment for each tooth, and will be described in part 2. [Correction added after online publication, 25th May 2012: sentence changed to include purpose of second part of study.]

Materials and methods

Subject material

Subjects included in this study were recruited from patients referred to the first author in a specialist endodontic practice for the management of suspected endodontic problems. The patients were seen consecutively between 1 October 2008 and 30 April 2009. All patients were examined clinically, and those diagnosed with signs of endodontic disease and scheduled for treatment were considered for inclusion in the study. Exclusion criteria included pregnant women, immunosuppressed patients, unrestorable teeth and teeth with periodontal probing depths >3 mm. Approval was sought and granted by the Guy's Research Ethics Committee, Guy's and St. Thomas Hospital National Health Service Trust (National Research Ethics Service, UK).

One hundred and fifty-one teeth in 132 patients fulfilled the aforementioned criteria, and these patients were asked to give their written consent to be involved in the study. A detailed verbal and written explanation of the purpose of the study was provided. The patients were advised that the diagnostic phase and treatment protocol would not adversely affect the outcome of treatment.

Radiographic technique

The clinical examination included exposure of periapical radiographs using a beam aiming device to

allow for standardization of the radiographs. All radiographs were taken with a dental X-ray machine (Planmeca Prostyle Intra, Helsinki, Finland) using a digital CCD (Schick Technologies, New York, NY, USA), and the exposure parameters were 66 kV, 7.5 mA and 0.10 s. The X-ray tube head, digital sensor and mandible were aligned to allow radiographs to be exposed using the paralleling technique. Small-volume (40 mm^3) CBCT scans (3D Accuitomo F170; J Morita Manufacturing, Kyoto, Japan) with exposure parameters 90 kV, 5.0 mA and 17.5 s were then taken of the area of interest. All CBCT scans were reformatted (0.125 slice intervals and 1.5 mm slice thickness).

Radiological assessment

The radiographic images were then assessed in two sessions as follows:

In session (1), the consensus panel assessed 50% of the periapical radiographs ($n = 76$) followed by 50% of CBCT scans ($n = 76$). In session (2), the consensus panel assessed the remaining 50% of CBCT scans ($n = 77$) followed by remaining 50% of periapical radiographs ($n = 77$).

The radiographs and CBCT images for sessions 1 and 2 were randomly ordered in each session. CBCT images that best confirmed the presence or absence of a radiolucent periapical lesion in the sagittal, coronal and/or axial planes were used as the starting point for each root to be observed. These images were selected by an endodontist who was experienced in using CBCT in endodontic therapy. The consensus panel also had access to the whole CBCT scan using CBCT software (One-Volume viewer; Morita) allowing them to scroll through any of the images. No further multiplanar reconstruction of the data (e.g. changing the orientation of the scan) was carried out. All images were assessed in a quiet, dimly lit room. The radiographs and CBCT images were viewed as a Keynote presentation (Apple, Cupertino, CA, USA) on laptop computers (MacBook Pro; Apple), which had a 15.5-inch LED backlit screen with a pixel resolution of 1680×1050 . Sessions (1) and (2) were divided into two separate viewing periods over the course of a day to minimize the likelihood of consensus panel fatigue. There was at least a 1-week interval between each of the main sessions.

The consensus panel included two endodontists who already had clinical experience in using CBCT. They were trained using examples of clinical radiographs and CBCT images with and without the presence of

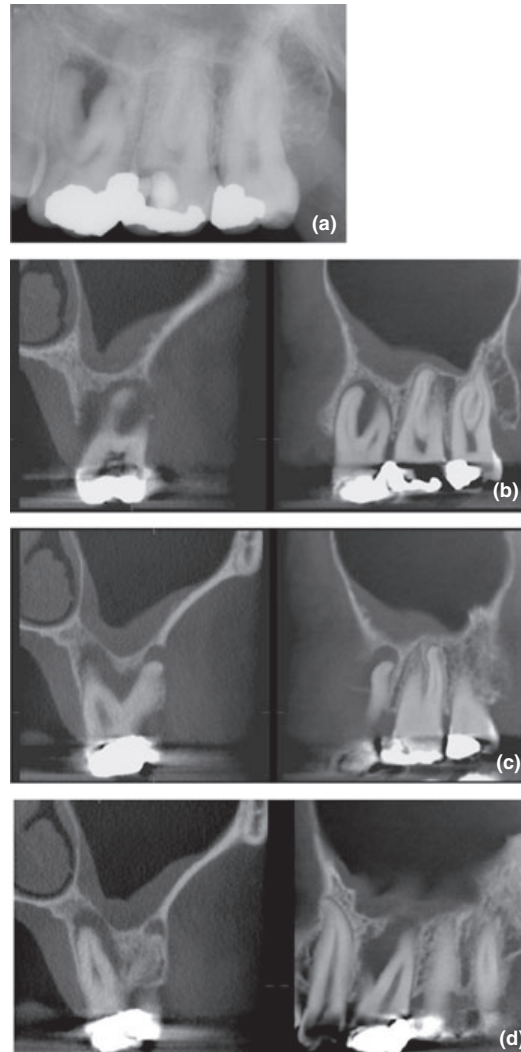


Figure 1 (a) Periapical radiograph of 26 reveals a periapical radiolucency associated with the mesio-buccal and palatal root, (b-d) coronal (left) and sagittal (right) reconstructed CBCT images reveal a periapical radiolucency associated with the (b) mesio-buccal, (c) disto-buccal-root and (d) palatal roots.

periapical lesions before embarking on the assessment. Before assessing the experimental material, the reliability of each member of the panel was assessed by asking them each to grade 30 periapical radiographs and 30 CBCT images for the presence and absence of periapical lesions. These radiographic images were not from experimental sample. The examiners were not involved in assessing or treating the patients.

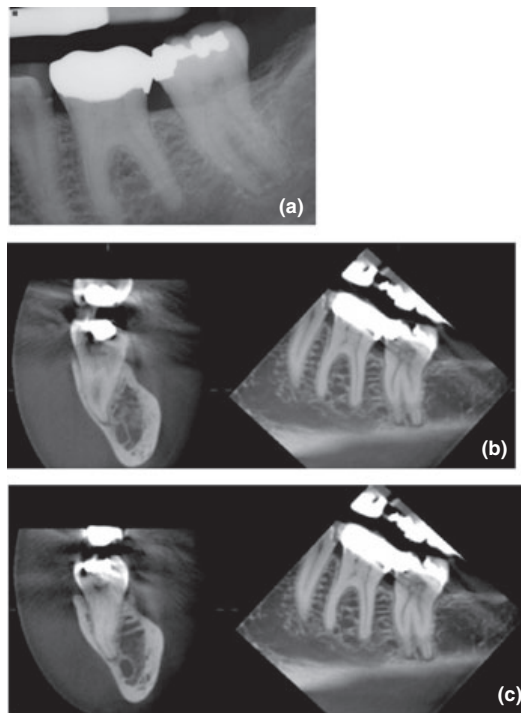


Figure 2 (a) Periapical radiograph of the 37 shows a healthy periapical tissues, (b-c) coronal (left) and sagittal (right) reconstructed CBCT images reveal periapical radiolucencies with the (b) mesial and (c) distal roots.

Table 1 Numbering of roots observed and identified during assessment

Tooth type	Root number		
	1	2	3
Incisors, canines, premolars ^a	Single root		
Premolars ^b	Buccal	Lingual/palatal	
Mandibular molars	Buccal	Mesio-lingual	Distal
Maxillary molars	Mesio-buccal	Disto-buccal	Palatal

^aPremolar with a single root canal.

^bPremolar with two root canals.

A periapical lesion was defined as a radiolucency associated with the radiographic apex of the root, which was at least twice the width of the periodontal ligament space (Low *et al.* 2008, Bornstein *et al.* 2011). With multirooted teeth, the presence or absence of a periapical lesion on each specific identifiable root was noted (Figs 1 and 2). This allowed like-pairs of specific roots identified using periapical radiographs and CBCT to be assessed for

the absence or presence of a periapical lesion. A consensus decision was reached for each of the radiographs and series of reconstructed CBCT images. An Excel (Excel 2010; Microsoft Corporation, Richmond, WA, USA) spreadsheet was created to log data.

Each root was identified by number, so that individual roots could be compared between radiological systems as pairs (Table 1). It was expected that in some cases, there would be a discrepancy in the number of roots being assessed between the two radiological systems.

Data analysis

StataTM software (Stata 11, College Station, TX, USA) was used to analyse the data. The sample size was determined by assessing previous similar research. It was calculated that 150 teeth would provide 80% power to show a 25% difference in the number of lesions identified as present between the radiological systems. Kappa analysis was used to assess the reproducibility of each of the two examiners of the consensus panel prior to the main study (Altman 1990). Comparison of periapical radiographs and CBCT images for the identification of the presence and absence of lesions was made using McNemar tests on paired single roots per tooth. Assessment of the presence and absence of the number of roots and periapical lesions per tooth was described, but not statistically tested.

Results

One hundred and fifty-one teeth in 132 patients were assessed in this study. The mean age of the patients was 44.7 (standard deviation 13.7), and the percentage of women and men was 58% and 42%, respectively.

The presence or absence of periapical lesions was detected in 273 pairs of roots with both periapical radiographs and CBCT images. Comparison of the 273 paired roots revealed that periapical lesions were present in 55 (20%) and absent in 218 (80%) roots when assessed with periapical radiographs. When the same 273 sets of roots were assessed with CBCT, lesions were present in 130 (48%) and absent in 143 (52%) roots.

An additional 76 (22%) roots were identified with CBCT alone. Therefore, the total number of roots detected with a periapical lesion present was 138 (40%), and 211 (61%) of roots had no periapical lesion in the 349 roots identified with CBCT. Owing to nonindependence, these data were not analysed statistically.

Table 2 Breakdown of agreement of periapical lesions (percentage) present (1) and absent (0) with intraoral radiographs (PA) and CBCT

	PA (0) CBCT (0)	PA (1) CBCT (0)	PA (1) CBCT (1)	PA (0) CBCT (1)	Paired roots
Total paired roots	137	6	49	81	273
Roots 1	64	4	40	43	151
Roots 2	51	2	6	32	91
Roots 3	22	0	3	6	31

Table 2 shows the number of paired roots of teeth assessed for periapical lesions in roots identified as 1, 2 and 3, respectively, using the schedule in Table 1. In all cases, CBCT images revealed a greater number of positive identifications than periapical radiographs ($P < 0.02$ to $P < 0.001$).

There was agreement on the absence of a lesion between the two radiological systems in 50% roots where paired roots were visualized. When assessing for the presence of a periapical lesions, there was agreement in 18% pairs of roots.

The Kappa values for interexaminer agreement after the training session were 0.878 and 0.837 for periapical radiographs and CBCT images, respectively.

Discussion

A reference standard to compare both radiological techniques would have been the ideal scenario. However, as this was a clinical study, this was not possible. The question arises: how valid were the diagnoses of the presence or absence of periapical lesions using either radiographic technique? *Ex vivo* studies in which the detection of simulated periapical lesions has been assessed with CBCT images and periapical radiographs have all confirmed the superior diagnostic ability of CBCT images over periapical radiographs (Stavropoulos & Wenzel 2007, Özen et al. 2009, Patel et al. 2009a,b, Soğur et al. 2009). These findings have been reinforced by more recent *in vivo* dog studies (Paula-Silva et al. 2009a,b). Intentionally created periapical lesions were induced around the roots of dog's teeth (one group had vital pulps to serve as a positive control). After 180 days (another group was left untreated to serve as a negative control), periapical radiographs and CBCT scans were taken after which the animals were sacrificed, and the root apices and surrounding periapical tissues were evaluated histologically (providing a reference standard). These studies confirmed that CBCT not only was more sensitive at detecting periapical lesions, but also had a higher overall accuracy when compared with periapical radiographs.

The two examiners who constituted the consensus panel were experienced in interpreting CBCT data, as well as appreciating the limitations of this technology including its poorer resolution. The use of a consensus panel has been used previously in studies assessing detection ability of periapical lesions to reduce interexaminer variation (Lofthag-Hansen et al. 2007, Low et al. 2008). Consensus panels surpass the accuracy of individual expert diagnoses where clinical information elicits diverse judgments. Viewing sessions were kept as short as practically possible, and all images were randomized both within and between sessions to reduce the potential effect of examiner fatigue.

The differential detection rate of periapical lesions with CBCT images compared with periapical radiographs was the same when two parallax radiographs (Lofthag-Hansen et al. 2007) and single periapical radiographs were taken (Low et al. 2008, Bornstein et al. 2011). Therefore, only one radiograph per tooth was included in this study.

A digital periapical radiographic system was used, and the image produced was dynamic and allowed it to be enhanced (contrast/brightness) to potentially improve its diagnostic yield (Kullendorf & Nilsson 1996). In addition, the effective dose for a digital periapical radiographic system is lower than for its film counterpart (Nair & Nair 2007). Several well-designed *ex vivo* studies have shown that there is no difference in the detection ability of artificially created periapical lesions using conventional X-ray films and digital sensors (Kullendorf & Nilsson 1996, Barbat & Messer 1998, Stavropoulos & Wenzel 2007, Özen et al. 2009). Enhancing the radiographic images (e.g. colourizing and inverting) with software was not carried out as it has not been shown to improve the detection of periapical lesions (Barbat & Messer 1998).

Antiglare LCD screens with a high pixel resolution were used to provide a high-quality image for the assessment of radiographs and CBCT images. There is evidence to suggest that LCD and high-resolution cathode ray tubes are equally effective for assessing CBCT images and digital radiographs (Baksi et al. 2009).

In this study, periapical radiographs and reconstructed CBCT images were assessed for their diagnostic ability in detecting radiographic signs of periapical periodontitis in 151 teeth planned for primary root canal treatment. Previous clinical studies have tended to focus on teeth that have already been root filled. In the study conducted by Lofthag-Hansen *et al.* (2007), 42 (91%) of the 46 teeth assessed with signs of endodontic disease had already been root filled. In two other studies, all the teeth had been root filled (Low *et al.* 2008, Bornstein *et al.* 2011). These studies focused on either posterior teeth (Lofthag-Hansen *et al.* 2007), maxillary posterior teeth (Low *et al.* 2008) or mandibular teeth alone (Bornstein *et al.* 2011). Estrela *et al.* (2008) assessed 83 untreated teeth including all tooth groups (i.e. anterior and posterior).

The results of this study revealed that periapical lesions were detected in only 55 (20%) of paired roots with periapical radiographs compared to 130 (48%) with CBCT images. That is, 28% more periapical lesions were detected with CBCT images when paired roots were compared. Periapical lesions were absent in 80% and 52% of paired roots assessed with radiographs and CBCT images, respectively. In addition, 76 roots were identified only with CBCT images; periapical lesions were present in 8 (10%) of these roots and absent in 68 (90%) [Correction added after online publication, 25th May 2012: The '(22)' after '76' has been deleted and '11%' has been changed to '10%']. These results concur with previous studies; Lofthag-Hansen *et al.* (2007) compared the prevalence of periapical periodontitis in 46 maxillary and mandibular posterior teeth and concluded that 20% more teeth had periapical lesions when assessed with reconstructed CBCT images compared with periapical radiographs. Low *et al.* (2008) found that 34% more periapical lesions were detected with reconstructed CBCT images than with intraoral radiography in 74 posterior maxillary teeth referred for periapical microsurgery. Estrela *et al.* (2008) assessed 83 untreated teeth diagnosed with an endodontic problem and found that the prevalence of radiological signs of periapical pathosis with periapical and reconstructed CBCT images was 36% and 75%, respectively, a 39% difference. Interestingly, the prevalence of periapical periodontitis was even lower with panoramic radiographs at only 22%. None of these studies specifically assessed paired roots.

One important question to be addressed is the potential presence of false positives in the CBCT images. Perhaps the ideal test would be to compare CBCT images of periapical tissues to histologic assessment in humans;

however, this is impossible as it is unethical to carry out such an investigation. Owing to cross-infection control regulations, it would also not be possible to undertake a similar study on human cadavers. However, a study on the diagnostic accuracy of small-volume CBCT and periapical radiography for the detection of very small simulated external inflammatory root resorption recently undertaken on dry mandibles demonstrated that CBCT images were far superior to periapical radiographs not only in terms of sensitivity (100% vs. 87%), but also, and more significantly, in terms of specificity (96% vs. 43%) with a negative predictive value (that is the ability to detect the absence of a lesion) standing at 86% for periapical radiographs and at 100% for CBCT images (Durack *et al.* 2011). Other studies also found higher negative predictive value for CBCT images compared with periapical radiographs (Patel *et al.* 2009b, Paula-Silva *et al.* 2009c).

Bornstein *et al.* (2011) found that there was a 74% agreement between periapical radiographs and CBCT images for the presence of a periapical lesion on paired roots of mandibular molar teeth. Although they did not compare paired roots, Low *et al.* (2008) found that there was 66% agreement between periapical radiographs and CBCT images for the presence of a periapical lesion. In the present study, there was only a 17.9% agreement between the radiological systems for the detection of the presence of a periapical lesion. The higher agreement in the previously published studies may be due to the fact that the teeth considered for inclusion in these studies had clinical and/or radiological signs of failed existing endodontic treatment. Therefore, the likelihood of a periapical lesion being detected would naturally be higher. In the present study, none of the teeth had been previously root treated and consisted of teeth with vital (e.g. gross caries, irreversible pulpitis) as well as infected necrotic pulps (e.g. chronic periapical periodontitis). In this study, 59 (39%) teeth were diagnosed to have irreversible pulpitis after clinical and conventional radiographic examination (i.e. no signs of a periapical radiolucency); however, 26 (44%) of these teeth had periapical radiolucencies when assessed with CBCT images. The presence of periapical lesion(s) detected only by CBCT images changes the endodontic diagnosis to a chronic periapical periodontitis, this may change treatment strategy, for example multiple visit treatment with calcium hydroxide inter-appointment dressing rather than single-visit treatment, and it also changes the prognosis of the treatment of which the patient needs to be informed (Ng *et al.* 2011).

The detection of periapical lesions using CBCT images will also help the clinician in avoiding direct or indirect pulp capping procedures on teeth that appear to have pulps with reversible pulpitis (i.e. respond positively to vitality testing and show no periapical lesions with intraoral radiographs).

The higher prevalence of periapical lesions detected by CBCT images is a result of the three-dimensional assessment of the teeth and surrounding tissues. The CBCT software allowed the clinician to select the most favourable orthogonal views for each specific root being assessed. This allows slices of data to be reconstructed without the overlying anatomical noise (i.e. cortical plate, zygomatic buttress and/or superimposed roots) obscuring the area of interest, and therefore, the status of the periapical tissues could be assessed. Slice angles were selected so that the coronal and sagittal views were parallel to the root being assessed, thus minimizing any distortion. These factors ultimately resulted in the presence or absence of periapical lesions being significantly more perceptible with CBCT images than with periapical radiographs. This is also why more roots could be assessed with CBCT images (Özen *et al.* 2009, Patel *et al.* 2009a, Paula-Silva *et al.* 2009a). The lower prevalence of periapical lesions with periapical radiography was because of the combination of anatomical noise, geometric distortion and the two-dimensional nature of the image produced (Estrela *et al.* 2008, Matherne *et al.* 2008, Paula-Silva *et al.* 2009b).

Each endodontic problem assessed in the present study was unique; therefore, the nature and location of the periapical lesions varied from case to case. However, it was considered important to carry out a clinical study, as the mechanically 'machined' periapical lesions used in previous *ex vivo* studies, although standardized, do not truly reflect the nature of real periapical lesions, which are generally irregularly shaped cavities. CBCT scans not only aided diagnosis, but facilitated the overall management of each case, for example the presence and location of root canals may be determined before treatment commenced (Tu *et al.* 2009, Neelakantan *et al.* 2010). Therefore, the specialist endodontist will know exactly where to look with the aid of the dental operating microscope, therefore reducing the time 'exploring' the pulp chamber looking for canal entrances.

The effective radiation dose to patients when using CBCT is higher than with conventional digital radiography, and there is huge variation in effective dose between CBCT scanners. In this study, the effective dose from CBCT scan was in the same order of magnitude to 2–3 standard periapical exposures (Arai *et al.* 2001,

Mah *et al.* 2003, Loubele *et al.* 2009). It is essential to justify the need for exposing a patient to radiation and then optimize the radiation dose. Therefore, the smallest field of view was selected in this study, thus keeping the radiation dose as low as reasonably achievable (Farman 2005, Patel & Horner 2009).

At present, CBCT is typically used to help diagnose poorly localized endodontic problems (for example irreversible pulpitis) and/or to treatment plan complex endodontic problems, for example multirooted teeth (Nair & Nair 2007, Patel 2009). In addition to revealing the true status of the periapical tissues, CBCT also provides other clinically relevant information, which cannot be readily elicited from intraoral radiographs, such as the number and configuration of root canals, proximity of adjacent neighboring anatomical structures and cortical plate topography (Rigolone *et al.* 2003, Estrela *et al.* 2008, Low *et al.* 2008, Matherne *et al.* 2008).

Conclusion

This study revealed that the periapical lesions were detected in only 55 (20%) of paired roots with periapical radiographs compared to 130 (48%) with CBCT images, that is a 28% more periapical lesions were detected with CBCT when paired roots were compared. In view of the superior accuracy of CBCT compared with periapical radiographs for diagnosing periapical periodontitis, it may be time to review the way that both epidemiological and outcome studies are performed as CBCT data offer a more accurate objective baseline value that has the potential to reduce false negatives so often detected with periapical radiographs. [Correction added after online publication, 25th May 2012: intraoral has been replaced with periapical throughout.]

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The detection of periapical pathosis using digital periapical radiography and cone beam computed tomography – Part 2: a 1-year post-treatment follow-up

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Abstract

Patel S, Wilson R, Dawood A, Foschi F, Mannocci F. The detection of periapical pathosis using digital periapical radiography and cone beam computed tomography – Part 2: a 1-year post-treatment follow-up. *International Endodontic Journal*, **45**, 1–13, 2012.

Aim Part 2 of this clinical study aims to compare the radiographic change in periapical status of individual roots determined using digital periapical radiographs versus cone beam computed tomography (CBCT) 1 year after primary root canal treatment and to determine the radiological outcome of treatment for each tooth.

Methodology Periapical radiographs and CBCT scans of 123 teeth in 99 patients assessed 1 year after completion of primary root canal treatment by a single operator were compared with their respective pre-treatment (diagnostic) periapical radiographs and CBCT scans. The presence or absence as well as the increase or decrease in size of existing periapical radiolucency was assessed by a consensus panel consisting of two calibrated examiners. The panel viewed the images under standardized conditions. Paired comparison of the outcome diagnosis of individual roots and teeth was performed using generalized McNemar's or Stuart–Maxwell test of symmetry analysis.

Results The 'healed' rate (absence of periapical radiolucency) for all roots combined was 92.7% using periapical radiographs and 73.9% for CBCT ($P < 0.001$). This rate increased to 97.2% and 89.4%, respectively, when the 'healing' group (reduced

size of periapical radiolucency) was included ($P < 0.001$). A statistically significant difference in outcome diagnosis of single roots was observed between DPA and CBCT in single-rooted teeth and the buccal or mesio-buccal roots of multi-rooted teeth ($P < 0.05$). Analysis by tooth revealed that the 'healed' rate (absence of periapical radiolucency) was 87% using periapical radiographs and 62.5% using CBCT ($P < 0.001$). This increased to 95.1% and 84.7%, respectively, when the 'healing' group (reduced size of periapical radiolucency) was included ($P < 0.002$). Outcome diagnosis of teeth showed a statistically significant difference between systems ($P < 0.001$). Reconstructed CBCT images revealed more failures (17.6%) in teeth with no pre-operative periapical radiolucencies compared with periapical radiographs (1.3%) ($P = 0.031$). In teeth with existing pre-operative periapical radiolucencies, reconstructed CBCT images also showed more failures (13.9%) compared with periapical radiographs (10.4%).

Conclusion Diagnosis using CBCT revealed a lower healed and healing rate for primary root canal treatment than periapical radiographs, particularly in roots of molars. There was a 14 times increase in failure rate when teeth with no pre-operative periapical radiolucencies were assessed with CBCT compared with periapical radiographs at 1 year.

Keywords: cone beam computed tomography, outcome of endodontic treatment, periapical intraoral radiographs.

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Introduction

The diagnostic outcome of root canal treatment is based on clinical and radiological findings (Friedman *et al.* 2003, Ng *et al.* 2011). It is not uncommon for disease to be clinically asymptomatic (Kirkevang & Hørsted-Bindlev 2002, Huuononen & Ørstavik 2002, Wu *et al.* 2009); therefore, radiological assessment is essential to objectively determine the outcome of treatment.

The results from diagnostic outcome studies allow the clinician to estimate the prognosis of the proposed root canal treatment. This can then be compared with the prognosis of possible alternative treatment strategies (for example, single-implant crown restorations); this essential information along with the benefits and risks of the various treatment options allows the patient to choose the most suitable treatment option for their individual needs (Friedman *et al.* 2003).

Periapical radiography is the technique of choice for diagnosing, managing and assessing endodontic disease (Patel *et al.* 2009a). Periapical periodontitis represents a reduction in the mineral density of the affected periapical bone in response to a localized inflammatory reaction to residual and/or re-infection within the root canal system (Bender 1982, Ørstavik & Larheim 2008); radiographically, this presents as a radiolucency. Conversely, the absence of a periapical radiolucency at the periapex of the root canal-treated roots indicates the absence of periapical periodontitis, suggesting that root canal treatment has been successful (Strindberg 1956, European Society of Endodontology 2006). This is the basis of how both non-surgical and surgical root canal treatments have been assessed for nearly 90 years (Blayney 1922, Peters & Wesselink 2002, Friedman *et al.* 2003, Chong *et al.* 2003, de Chevigny *et al.* 2008).

Ex vivo and *in vivo* studies have confirmed that periapical radiography is of limited use for detecting periapical radiolucencies (Bender & Seltzer 1961, Bender 1997, Jorge *et al.* 2008, Paula-Silva *et al.* 2009a). Small or early periapical lesions confined to the cancellous bone are not easily seen on radiographs, owing to the overlying cortical plate masking the periapical lesion; this phenomenon is known as 'anatomical noise' (Revesz *et al.* 1974, Gröndahl & Huuononen 2004). Periapical radiolucent lesions are usually only diagnosed when there has been perforation or erosion of the overlying cortical plate (Bender & Seltzer 1961, Jorge *et al.* 2008, Patel *et al.* 2009b). Further limitations include the compression of the complex three-dimensional anatomy of the area being radiographed into a two-dimensional shadowgraph

and geometric distortion. These limitations mean that radiographs cannot consistently reveal the true nature and location of presence or absence of apical periodontitis (Van Vorde & Bjørndahl 1969, Forsberg & Halse 1994, Velvart *et al.* 2001, Paula-Silva *et al.* 2009a).

Several studies have been published confirming the improved diagnostic accuracy of cone beam computed tomography (CBCT) over conventional radiography for diagnosing periapical periodontitis (Lofthag-Hansen *et al.* 2007, Low *et al.* 2008, Estrela *et al.* 2008, Bornstein *et al.* 2011). Recently, Paula-Silva *et al.* (2009b) assessed the diagnostic outcome of root canal treatment performed in dogs using periapical radiographs and CBCT, they concluded that the treatment outcome varied according to the radiological system used; a favourable outcome was 79% and 35% with periapical radiographs and CBCT, respectively (Paula-Silva *et al.* 2009b). Small field of view scans are best suited for diagnosing and managing of endodontic problems (Patel 2009). To date, there have been no published studies comparing the diagnostic outcome of root canal treatment in humans using pre-diagnostic and follow-up radiographs.

The purpose the second part of this study was to determine the radiographic change in periapical status of individual roots using periapical radiographs and CBCT at 1 year after primary root canal treatment and to determine a radiological outcome of treatment for each tooth.

Materials and methods

Subject material

The subject material has been described in part 1 of this study (Patel *et al.* 2012). Diagnostic digital periapical radiographs and CBCT scans of teeth treatment planned for primary root canal treatment were taken of 151 teeth in 132 patients. The patients were then reviewed 1 year post-operatively (see later). Only patients whose teeth fulfilled the inclusion criteria were asked to participate in the study (Patel *et al.* 2012). Approval was sought and granted by the Guy's Research Ethics Committee, Guy's and St. Thomas Hospital National Health Service Trust (National Research Ethics Service, England) for this study.

Radiographic technique

The 1-year follow-up assessment included exposure of digital periapical radiographs and CBCT scans as described in part 1 of this study (Patel *et al.* 2012).

Primary root canal treatment procedure

All primary root canal treatments were carried out by a single operator in a single visit. The tooth to be treated was anaesthetized and isolated under rubber dam. Before starting primary root canal treatment, plaque deposits, calculus, caries and existing restorations were removed after which the restorability of the underlying tooth structure was assessed. In instances where minimal tooth structure was left, the tooth was restored with a glass ionomer foundation (Fuji IX glass ionomer cement; GC America, Alsip, IL, USA) to allow isolation with rubber dam.

All primary root canal treatments were performed using sterilized, single use endodontic files. A standardized protocol was used to disinfect and fill the root canal system. Each canal was initially negotiated with size 08 and 10 stainless steel Flexofiles[®] (Dentsply Maillefer, Ballaigues, Switzerland). The balanced force instrumentation technique was used to negotiate each canal to its provisional working length. The definitive working length was determined with the aid of an apex locator (Root ZX II[®]; J Morita, Kyoto, Japan) in conjunction with measurements using the CBCT software (I-Dixel[®]; J Morita). The working length was always 1 mm short of the '0' apex locator reading length. Canals were then prepared to at least a size 20 Flexofile[®] to the working length, after which ProTaper[®] nickel-titanium rotary instruments (Dentsply Maillefer) at 300 RPM were used in a crown-down approach to prepare each root canal to at least a F1 master apical rotary file. Canals were continuously irrigated with 2% sodium hypochlorite (Chloraxid[®] 2.0%; PPH Cerkamed, Sandomierska, Poland) for 30 min, the irrigant was replenished every 3–4 min after which it was immediately agitated with an appropriately selected gutta-percha point extending to 2 mm short of the working length for approximately 30 s. The root canals were then irrigated with 15% ethylenediaminetetraacetic acid (EDTA) (ENDO-Solution[®]; PPH Cerkamed) followed by a final irrigation with sodium hypochlorite. The irrigant was ultrasonically energized with a size 25 Endo-activator[®] (Dentsply Maillefer) for 1 min. The canals were then dried with paper points and filled with gutta-percha and AH sealer (Dentsply Maillefer) using a warm vertical compaction technique. The teeth were then restored with permanent glass ionomer cores (Fuji IX[®] glass ionomer cement) or composite resin (Herculite ultra[®]; Kerr corporation, Orange, CA, USA) depending on the referring practitioner's preference.

A dental operating microscope was used during treatment, and all teeth requiring permanent, cuspal-coverage restorations were restored by the referring practitioner within 1 month of completion of the root canal treatment.

Follow-up assessment

All patients were contacted approximately 11 months later to schedule a 12-month review appointment with the first author. Clinical assessment included tenderness to percussion, mobility and checking for increased periodontal probing depths. The soft tissues were also assessed for tenderness to palpation, signs of erythema and sinuses; the integrity and marginal fit of the definitive restoration were also assessed. Periapical radiographs and CBCT radiographic assessment was carried out as described previously in part 1 of this study (Patel *et al.* 2012).

Radiological assessment

Calibration of examiners

Assessment of the data was carried out by a consensus panel that consisted of the same 2 endodontists described in part 1 of this study (Patel *et al.* 2012). The first author was not involved in the assessment of the radiographic images. Both members of the consensus panel were not aware of the purpose of the study. As several months had elapsed between the assessment of radiographic images in part 1 and part 2 of this study, the examiners were retrained using 50 examples of periapical radiographs and CBCT reconstructed images with and without the presence of periapical radiolucencies before embarking on the assessment. Before assessing the experimental material, the inter-examiner agreement of the consensus panel members was assessed by asking them to grade the outcome of root canal treatment of 20 cases using periapical radiographs and reconstructed CBCT images. These cases were not part of the experimental material. The radiographs and CBCT data sets were viewed as Keynote[®] presentations (Apple, Cupertino, CA, USA) on laptop computers (MacBook Pro[®]; Apple Computer Inc.) with 15.5-inch Light-emitting diode (LED) backlit screen with a pixel resolution of 1680 × 1050.

The radiographic diagnostic outcome of each root was classified into six categories:

1. New periapical radiolucency;
2. Enlarged periapical radiolucency;
3. Unchanged periapical radiolucency;

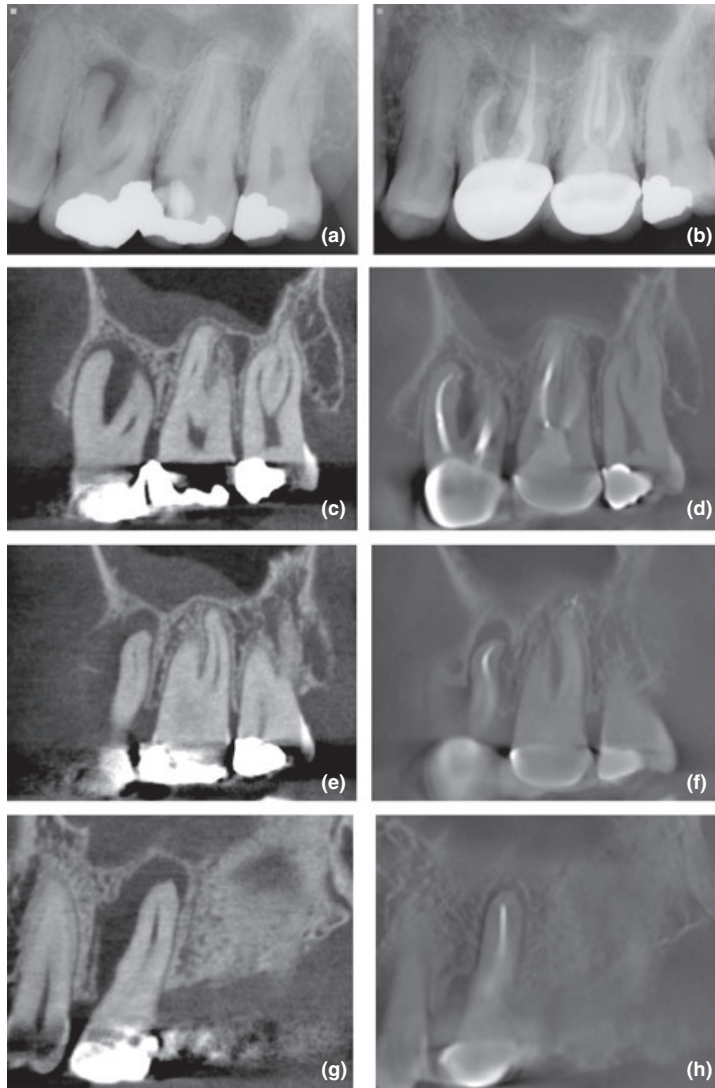


Figure 1 (a) pre-operative radiograph of 26 revealing periapical radiolucencies on mesio-buccal and palatal root, (b) 1-year follow-up radiograph reveals a significant reduction in size of the periapical radiolucency on the mesio-buccal root (outcome 4), complete resolution of periapical radiolucency on the palatal root (outcome 5), and no change in the healthy periapical status of the distobuccal root (outcome 6). (c–h) reformatted cone beam computed tomography (CBCT) images reveal pre-operative periapical radiolucencies on mesio-buccal, disto-buccal and palatal roots, which 1 year later have reduced in size on the mesio-buccal and disto-buccal roots (outcome 4), and has resolved (outcome 5) on the palatal root. Radiographic and CBCT tooth outcome is 5 and 4, respectively.

4. Reduced periapical radiolucency;
5. Resolved periapical radiolucency;
6. Unchanged healthy periapical status (no radiolucency before and after treatment).

For the purposes of clinically defined outcomes, a 'healed' outcome (i.e. strict criterion) was defined where a periapical radiolucency was absent (outcome 5 and 6) and a 'healing' outcome (i.e. loose criterion) where a radiolucency had reduced in size or was absent (outcome 4–6).

In multi-rooted teeth, the diagnostic outcome for the tooth was assessed using the root with the 'worst' diagnostic outcome category, whilst for single-rooted

teeth the diagnostic outcome category for the root was also used for tooth outcome. In the event of multi-rooted teeth with the periapical status of one root classified as 'category 1' and the other root classified as 'category 2', the category 1 was considered the 'worst case' scenario. An Excel® (Excel 2010; Microsoft, Richmond, WA, USA) spreadsheet was created to log data. All data were anonymized. A series of up to 10 CBCT reconstructed images that best confirmed the presence or absence of a radiolucent periapical radiolucency(s) in the sagittal, coronal and/or axial planes was used as the starting point for each tooth observation. The consensus panel also had access to the raw

Figure 2 (a) pre-operative radiograph of 36, and (b) 1-year follow-up radiograph revealing healthy periapical tissues for both roots (outcome 6). (c-d) reformatted cone beam computed tomography (CBCT) images reveal no pre-operative periapical radiolucencies on either the mesial or distal roots, but 1 year later, there are new periapical radiolucencies on both roots (outcome 1). Radiographic and CBCT tooth outcome is 6 and 1, respectively.

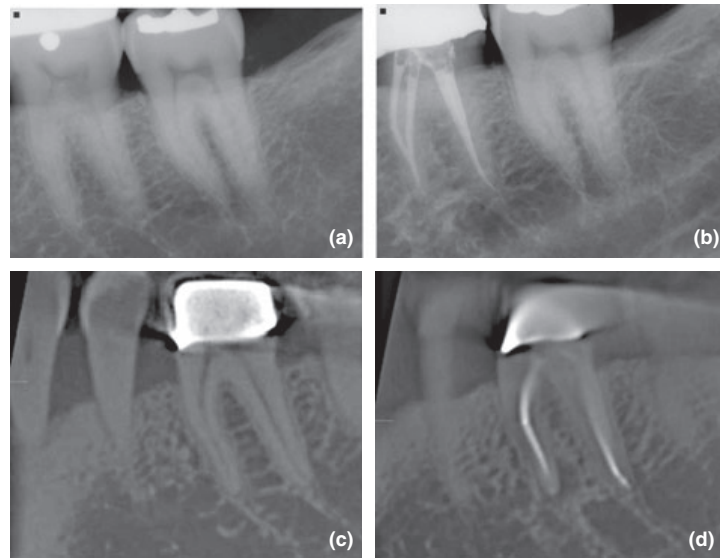
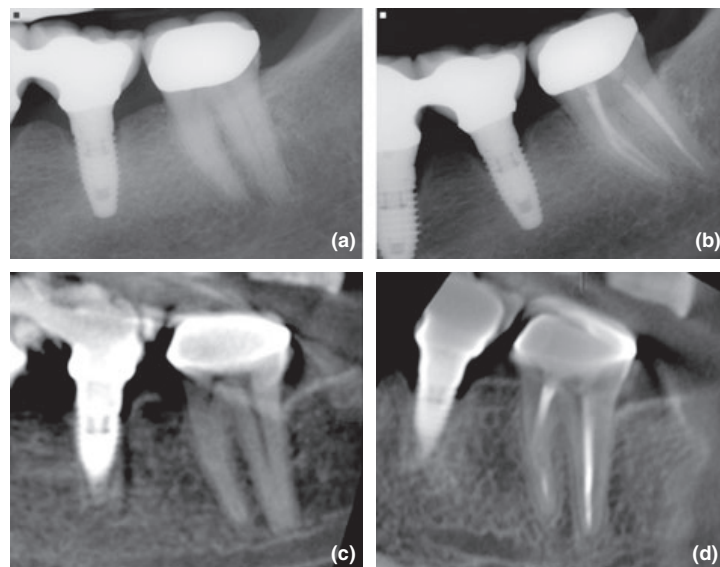


Figure 3 (a) pre-operative radiograph of 37 and, (b) 1-year follow-up radiograph revealing healthy periapical tissues (outcome 6 for both roots). (c-d) reformatted cone beam computed tomography (CBCT) images reveal the no pre-operative periapical radiolucencies on either the mesial or distal roots, and 1 year later, the periapical radiolucencies are still within normal limits (outcome 6). Radiographic and CBCT tooth outcome is 6.



CBCT data using CBCT software (one-Volume viewer, Morita) allowing them to scroll through any of the orthogonal scans. All images were assessed in a quiet dimly lit room. All CBCT data sets were assessed using the same computer monitor(s).

Assessment of experimental data

The experimental material was assessed jointly by both examiners. The radiographic images were then assessed in three sessions as follows:

In the first session, the consensus panel assessed 50% of the periapical radiographs ($n = 61$) followed by 50% of CBCT reconstructed images ($n = 62$); in the second session, the consensus panel assessed the remaining 50% of CBCT reconstructed images ($n = 61$) followed by the remaining 50% of periapical radiographs ($n = 62$). Periapical radiographs and CBCT images of the same tooth were not assessed in the same session; in the third session, 70 periapical radiographs and 70 series of CBCT images were assessed to determine intra-consensus panel agreement.

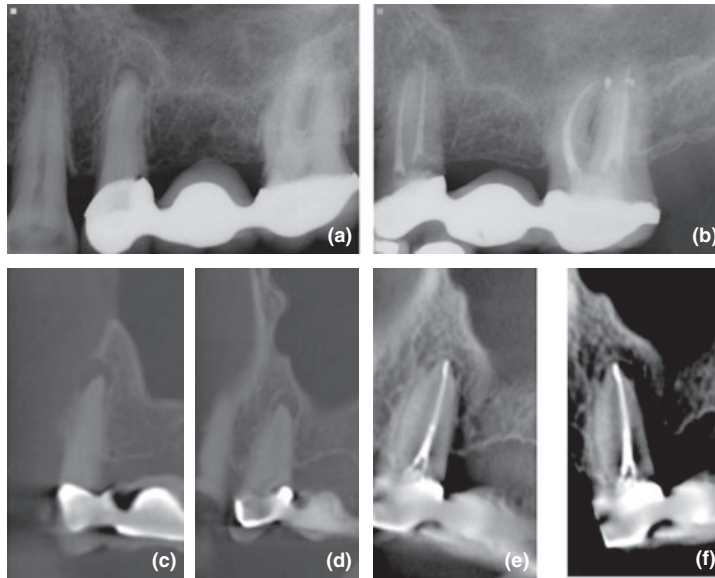


Figure 4 (a) pre-operative radiograph of 24 revealing periapical radiolucencies on the buccal and palatal roots, (b) 1-year follow-up radiograph reveals complete resolution of periapical radiolucencies (outcome 5). (c–d) Reformatted cone beam computed tomography (CBCT) images reveal pre-operative periapical radiolucencies on the buccal and palatal roots, which 1 year later have completely resolved (outcome 5). Radiographic and CBCT tooth outcome is 5.

The radiographic images were assessed as described in the calibration session (Table 1). There was at least a 1-week interval between each session, and the images within each session were randomly ordered. The pre-operative and the 1-year follow-up periapical radiographs of each case were viewed together to allow the examiners to assess the images for the presence, absence or change (increase/decrease) in size of an existing periapical radiolucency (Figs 1–4). This was also done when the CBCT reconstructed images were assessed. The first and second sessions were divided into at least two separate viewing periods over the course of a day to minimize the likelihood of consensus panel fatigue. The periapical tissue status category 5 and 6 were given when there was an intact lamina dura with a maximum widening of 2 mm immediately adjacent to any flush or extruded root filling material.

Data analysis

Data were analysed using Stata™ software (Stata 11, College Station, TX, USA). Kappa analysis was used to assess the inter-examiner agreement prior to the main study and the intra-consensus panel agreement during the study (Tables 2 & 3). Comparison of periapical radiographs with reconstructed CBCT images for diagnosis of outcome by individual roots and by tooth was performed using the generalized McNemar's or Stuart–Maxwell test of symmetry for testing marginal homogeneity with multiple paired categories.

Comparison of diagnostic outcome by tooth type within and between radiographic systems was performed using chi-square tests. Anterior teeth included incisors and canines and posterior teeth included premolar and molar teeth. Where multiple contrasts were performed on the same data set, as with the comparison of anterior/posterior and maxillary/mandibular sites, the *P* value for statistical significance was adjusted ($P < 0.01$). Otherwise, $P < 0.05$ was accepted as indicating statistical significance.

Results

Ninety-nine of the original 132 patients from part 1 of this study were reviewed (75% recall rate), this included 123 teeth (Figure 5) of the original 151 teeth initially treated (82%). The percentage of women and men was 58% and 42%, respectively. The mean age of the patients was 44.5 years (SD 13.7) and ranged from 9 to 76 years of age.

Clinical assessment

None of the patients presented with any symptoms at 1 year post-treatment, and they all confirmed that they were not avoiding masticating with the root canal-treated tooth (i.e. the root canal-treated tooth was functional). Clinical examination of all the teeth and the surrounding tissues was unremarkable, and all coronal restorations were intact.

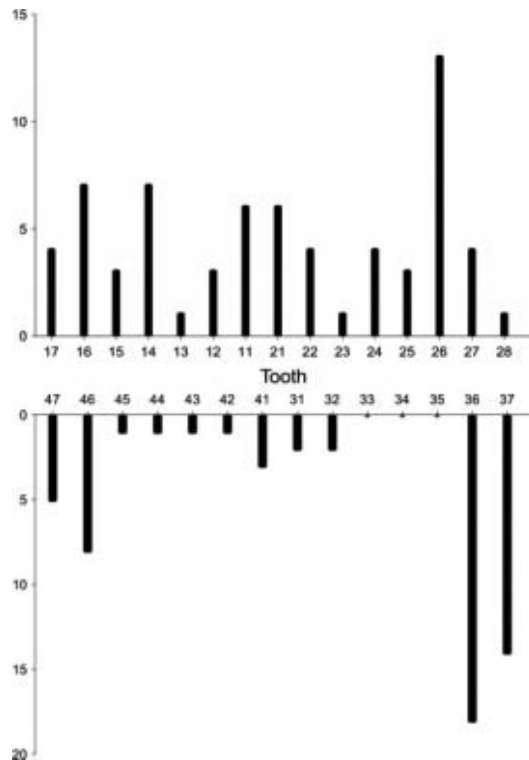


Figure 5 Frequency distribution of teeth ($n = 123$) assessed 1 year post-root canal treatment.

Table 1 Numbering of roots observed and identified during assessment

Tooth type	Root number		
	1	2	3
Incisors, canines, premolars ^a	Single root		
Premolars ^b	Buccal	Lingual/Palatal	
Mandibular molars	Buccal	Mesio-lingual	Distal
Maxillary molars	Mesio-buccal	Disto-buccal	Palatal

^aPremolar with a single root canal.

^bPremolar with two root canals.

A statistically significant difference in outcome diagnosis of single roots was observed between periapical radiographs and CBCT in roots 1 and 2 ($P = 0.03$ and

Table 2 Kappa values (95% confidence intervals) for pre-study inter-examiner agreement on outcome diagnosis using periapical radiography (DPA) and cone beam computed tomography (CBCT) ($n = 20$)

System	Root 1	Root 2	Root 3
DPA	0.837 (0.813–0.919)	0.440 (0.155–1.000)	– ^a
CBCT	1.000 (1.000–1.000)	0.726 (0.634–1.000)	0.588 (0.093–1.000)

^aToo few values for analysis.

$P < 0.001$, respectively). The difference for root 3 did not reach statistical significance ($P = 0.1$) (Table 4 & 5). A statistically significant difference in outcome diagnosis of teeth was observed between periapical radiographs and CBCT ($P < 0.001$) (Table 6).

Teeth with no pre-treatment periapical radiolucencies (Table 7) showed significantly ($P < 0.001$) less failures (1.3%) with periapical radiographs compared with reconstructed CBCT images (17.6%). Table 7 shows the combined prevalence of enlarged and unchanged periapical radiolucencies was 10.4% for periapical radiographs and 13.9% for reconstructed CBCT images. This difference was not statistically significant ($P = 0.8$).

Comparison within both radiographic systems revealed statistically significant differences (chi-square analysis) in outcome diagnoses by tooth group for both periapical radiographs ($P = 0.002$) and CBCT reconstructed images ($P = 0.01$) (Table 8). However, two-group comparisons, with P values adjusted for multiple contrasts, showed few differences, indicating only that maxillary and mandibular posterior teeth both differed significantly from maxillary anterior teeth when diagnostic outcome was assessed by periapical radiographs; and maxillary posterior teeth differed significantly from mandibular anterior teeth when outcome was diagnosed using CBCT ($P < 0.01$).

Comparison between periapical radiographs and reconstructed CBCT images revealed a statistically significant difference ($P = 0.002$) in the number of occurrences of each diagnostic outcome for maxillary posterior teeth (Table 8). There was also a difference in outcome for mandibular anterior teeth between the two radiographic systems that approached statistical significance ($P = 0.04$). There was no difference in outcome for mandibular posterior ($P = 0.1$) and maxillary anterior ($P = 0.7$) teeth between periapical radiographs and CBCT reconstructed images.

Discussion

In this prospective clinical study, the radiographic diagnostic outcome of root canal treatment was assessed using periapical radiographs and recon-

Table 3 Kappa values (95% confidence intervals) for intra-consensus panel agreement on outcome diagnosis using periapical radiographs (DPA) and cone beam computed tomography (CBCT) 1 week apart ($n = 70$)

System	Root 1	Root 2	Root 3
DPA	0.768 (0.651–0.886)	0.736 (0.403–0.856)	0.776 (0.750–0.857)
CBCT	0.915 (0.879–0.980)	0.916 (0.915–0.959)	0.858 (0.821–1.000)

Table 4 Frequency distribution of each periapical outcome of endodontic treatment for paired roots assessed using periapical radiographs (DPA) and CBCT

Outcome	Root 1		Root 2		Root 3		Total 1 + 2 + 3	
	DPA	CBCT	DPA	CBCT	DPA	CBCT	DPA	CBCT
1 – new lesion	0	7	1	4	0	1	1	12
2 – enlarged lesion	0	5	0	1	1	0	1	6
3 – unchanged lesion	4	5	0	0	0	0	4	5
4 – reduced lesion	10	22	0	9	0	3	10	34
5 – resolved lesion	28	31	9	16	1	3	38	50
6 – no lesion before/after treatment	81	53	60	40	23	18	164	111
Total	123	123	70	70	25	25	218	218

CBCT, cone beam computed tomography.

Table 5 Percentage of combined outcomes indicating healing, no change or failure for individual roots (data derived from Table 4) assessed with periapical radiographs (DPA) and CBCT

Outcome categories	Root 1		Root 2		Root 3		Total 1 + 2 + 3	
	DPA	CBCT	DPA	CBCT	DPA	CBCT	DPA	CBCT
1/2/3 – failed	3.3	13.8	1.4	7.1	4	4	2.8	10.6
1/2 – new/larger lesions	0	9.8	1.4	7.1	4	4	0.9	8.3
3 – no change in size	3.2	4.1	0	0	0	0	1.8	2.3
4/5/6 – healing (includes healed)	96.7	86.2	98.6	92.9	96	96	97.2	89.4
4 – healing	8.1	17.9	0	12.9	0	12	4.6	15.5
5 – healed	22.8	25.2	13.7	22.9	4	12	17.4	23.0
5/6 – healed	88.6	68.3	98.6	80	96	84	92.7	73.9

CBCT, cone beam computed tomography.

Outcome of each tooth was assessed using the following criteria: 1-new lesion, 2-enlarged lesion, 3-unchanged lesion, 4-reduced lesion, 5-resolved lesion, 6-no lesion before or after treatment.

Table 6 Frequency distribution (percentage) of outcome of treatment for each tooth assessed using periapical radiographs (DPA) and cone beam computed tomography (CBCT)

Outcome	DPA	CBCT
1 – new lesion	1 (0.8)	9 (7.3)
2 – enlarged lesion	1 (0.8)	5 (4.1)
3 – unchanged lesion	4 (3.3)	5 (4.1)
4 – reduced lesion	10 (8.1)	27 (22.0)
5 – resolved lesion	33 (26.8)	35 (28.5)
6 – no lesion before/after treatment	74 (60.2)	42 (34.0)
Total	123 (100)	123 (100)

structed CBCT images. To the author's knowledge, this is the first published prospective, longitudinal clinical study in humans comparing endodontic treatment

outcome using both radiographic techniques before treatment and at a 1-year review. A recent retrospective clinical study assessed endodontic outcome with periapical radiographs and reconstructed CBCT images but no pre-treatment CBCTs were taken (Liang *et al.* 2011).

An important aspect that has to be addressed is the potential presence of false readings in the reconstructed CBCT images, considering that the resolution of CBCT images is lower than that of periapical radiographs. It would have been unethical to undertake a histologic assessment of the patient's periapical tissues, and it was not possible owing to cross-infection control regulations, to undertake a similar study on cadavers. However, a study on the diagnostic accuracy of small volume CBCT and periapical radiographs for the

Table 7 Outcome of treatment for each tooth as a number (percentage) with periapical radiographs (DPA) and cone beam computed tomography (CBCT) of teeth with (a) no pre-operative peri-apical radiolucency, ($P < 0.001$ chi-square test) (b) existing peri-apical radiolucency, ($P = 0.759$ chi-square test)

	DPA	CBCT
(a)		
Teeth with new lesions (outcome 1)	1 (1.3)	9 (17.6)
Teeth with no new lesions (outcome 6)	74 (98.7)	42 (82.4)
Total number of teeth showing no pre-operative radiolucency	75	51
(b)		
Teeth with reduced lesions (outcome 4 and 5)	43 (89.6)	62 (86.1)
Teeth with enlarged/unchanged lesions (outcome 2 and 3)	5 (10.4)	10 (13.9)
Total number of teeth showing pre-operative radiolucency	48	72

Outcome of each root was assessed using the following criteria: 1-new periapical lesion, 6-no periapical before or after treatment. With multi-root teeth, the 'worst' root determined the outcome.

Outcome of each root was assessed using the following criteria: 2-enlarged periapical lesion, 3-unchanged periapical lesion, 4-reduced periapical lesion, 5-resolved periapical lesion.

detection of artificially created periapical lesions on dry mandibles demonstrated that CBCT was far superior to periapical radiographs in terms of sensitivity (100% vs. 25%, respectively); however, both systems gave perfect results (100%) for specificity (Patel *et al.* 2009b), a finding confirmed by Paula-Silva *et al.* (2009c).

The 6-point classification used in the present study allowed the assessment of the nature of existing periapical lesions in more detail. The 1-year follow-up

of patients in the present study conformed to quality guidelines for endodontic treatment (European Society of Endodontology 2006). The terms 'effective' and 'ineffective' root canal treatment have been suggested to replace 'healed/healing' and 'failure', respectively (Wu *et al.* 2011a,b). This terminology may be a more pragmatic approach to assess (and manage) the outcome of root canal treatment.

The study is ongoing and patients will continue to be recalled on a periodic basis and the data analysed. Although a higher recall at review would have been ideal, the 75% was acceptable. The patients who were contacted but declined a review appointment were all asked whether their root canal-treated tooth was symptomatic and whether they were actively using it; all reported no symptoms and confirmed that the tooth was functional. Patients who were not reviewed fell into one of two categories. First, those who declined a review appointment as they felt they could not justify and/or afford the time and/or indirect costs of attending. The second group consisted of patients who could not be contacted as they either did not return messages or had moved away without leaving forwarding contact details. The problems of recalling patients in clinical studies are well documented (Sprague *et al.* 2003, Ross *et al.* 2009). Reasons often cited for failing or the inability to attend review appointments include: expense (for example, transport), the transient nature of the working population in large cities and lack of time, including travelling to and from work/home (Friedman *et al.* 2003, Sprague *et al.* 2003, Ng *et al.* 2011).

As in part 1 of this study, when assessing multi-rooted teeth, the periapical status on each identifiable

Table 8 Frequency distribution (percentage) of outcome of endodontic treatment with periapical digital radiography (DPA) and cone beam computed tomography (CBCT) for maxillary posterior, mandibular posterior, maxillary anterior and mandibular anterior teeth

Outcome category ^a	DPA				CBCT			
	Tooth type				Tooth type			
	Maxillary posterior	Mandibular posterior	Maxillary anterior	Mandibular anterior	Maxillary posterior	Mandibular posterior	Maxillary anterior	Mandibular anterior
1	0 (0.0)	9 (2.1)	0 (0.0)	0 (0.0)	3 (6.5)	6 (12.8)	0 (0.0)	0 (0.0)
2	1 (0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (4.4)	2 (4.3)	0 (0.0)	1 (11.1)
3	0 (0.0)	3 (6.4)	0 (0.0)	1 (11.1)	3 (6.5)	2 (4.3)	0 (0.0)	0 (0.0)
4	3 (6.5)	4 (8.5)	3 (14.3)	0 (0.0)	14 (30.4)	8 (17.0)	5 (23.8)	0 (0.0)
5	10 (21.7)	9 (19.2)	12 (57.1)	2 (22.2)	5 (10.9)	13 (27.7)	10 (47.6)	7 (77.8)
6	32 (69.6)	30 (63.8)	6 (28.6)	6 (66.7)	19 (41.3)	16 (34.0)	6 (28.6)	1 (11.1)
Total	46 (100)	47 (100)	21 (100)	9 (100)	46 (100)	47 (100)	21 (100)	9 (100)

^aOutcome was assessed using the following criteria: 1-new lesion, 2-enlarged lesion, 3-unchanged lesion, 4-reduced lesion, 5-resolved lesion, 6-no lesion before or after treatment.

root was noted, thus allowing the outcome of matching pairs of roots using periapical radiographs and CBCT reconstructed images to be assessed (Patel *et al.* 2012).

A single periapical radiograph was assessed for each tooth, this is similar to other published work assessing outcome of root canal treatment (Friedman *et al.* 2003, de Chevigny *et al.* 2008). This was also consistent with the assessment of the periapical status before treatment commenced in part 1 of this paper (Patel *et al.* 2012). In the present study, the increased or decreased size of a periapical radiolucency at the 1-year follow-up was compared with any pre-treatment radiolucency. This type of visual comparison has been used in the majority of outcome studies (de Chevigny *et al.* 2008, Ng *et al.* 2011). Recently, volumetric assessment of periapical radiolucencies visualized on CBCT images has been carried out (Paula-Silva *et al.* 2009a). However, the accuracy of these *in vivo* volumetric measurements of periapical radiolucencies has not been confirmed.

The consensus panel agreement was acceptable; at least where sufficient roots were presented for diagnosis, the low Kappa value for root 3 was owing to the small sample size. However, agreement for the intra-consensus panel assessment, which was used in the main study, was excellent. The examiners were both experienced in the use of CBCT for managing endodontic problems including detecting radiographic signs of periapical periodontitis. Both radiographic techniques were standardized as were the viewing sessions; therefore, minimizing the overall observer variation owing to faults in radiographic technique, knowledge and judgment (Robinson *et al.* 2005, Brealey & Westwood 2007). As would be expected, inter-examiner agreement with CBCT was higher than for periapical radiographs, confirming its superior reliability. This is in agreement with the results reported by other studies assessing periapical radiolucencies (Soğur *et al.* 2009, Lennon *et al.* 2011, Liang *et al.* 2011). The intra-consensus panel agreement also followed a similar trend of being higher with CBCT (0.858–0.915) compared with periapical radiographs (0.736–0.776). These levels of agreement were excellent (Landis & Koch 1977). Anatomical noise and the compression of three-dimensional anatomical structures were probably the major contributory factors that resulted in the poorer kappa scores with periapical radiographs. Ideally, having more examiners would have made the present study stronger. However, it would have been very difficult to recruit more examiners who would have been willing to assess over 1000 reconstructed CBCT images and data sets. Previous prospective

endodontic outcome studies have also used one or two examiners (Friedman *et al.* 2003, Ng *et al.* 2011).

Several investigations have shown that inter-examiner agreement can be as little as 25% between examiners (Tewary *et al.* 2011) and one 'outlier examiner' can skew results (Goldman *et al.* 1972, Tewary *et al.* 2011). As with part 1 of this study, viewing sessions were kept as short as practically possible to reduce the likelihood of examiner fatigue.

The prevalence of unresolved periapical radiolucency after primary root canal treatment was significantly higher when teeth were assessed with CBCT compared with periapical radiographs regardless of whether the data were assessed by individual roots or by tooth. Previous studies, using periapical radiographs alone, have concluded that diagnostic outcome results were similar regardless of whether outcome was assessed as 'tooth' or 'root' units (Hoskinson *et al.* 2002, Ng *et al.* 2011); a similar conclusion was also reached in this study.

More roots appeared not to have changed from their pre-treatment healthy periapical status (outcome 6) with periapical radiographs (75.2%) compared with CBCT (50.9%), that is, they retained their healthy pre-treatment periapical status.

Fourteen times more new periapical radiolucencies (outcome 1) were detected with CBCT compared with periapical radiographs in teeth for outcome 1, this may be partially explained by the fact that new periapical radiolucencies are clearly very small in size and more easily detected by the most sensitive technique.

Interestingly, these teeth were all molars, and only 1 was associated with sealer extrusion, this suggests that foreign body reactions were not associated with the presence of radiolucencies in teeth that did not show any periapical radiolucency pre-operatively and that the technical challenges associated with the treatment of molars might have reduced the success rate in these teeth. It is possible that these radiolucencies are transient; the aim is to review all these teeth at 2, 3 and 4 years post-treatment which will provide a better understanding of the long-term dynamics of periapical healing. The prevalence of failure of primary root canal treatment in teeth with pre-treatment periapical radiolucencies (outcome 2 and 3) was higher with CBCT (13.9%) compared with periapical radiographs (10.4%).

The results from the periapical radiographs assessment in the present study is in agreement with the literature (Friedman *et al.* 2003, de Chevigny *et al.* 2008, Ng *et al.* 2008) that associates the absence of a

pre-operative periapical radiolucency with a higher success rate of primary root canal treatment.

Teeth with no pre-operative periapical radiolucency can be either teeth presenting with a carious exposures, irreversible pulpitis and virtually no infection within the root canal space or teeth with a root canal infection that is not sufficient to provoke an inflammatory reaction of the periapical tissues (Ricucci et al. 2009). All nine teeth with failed root canal treatment in outcome 'outcome 1' had vital pulp tissue. It is unlikely that endodontic treatment was unable to remove the few bacteria that might have been present within the root canal space of these vital and/or necrotic cases. It is possible that bacteria are introduced into the root canal space during the root canal treatment itself despite the use of rubber dam, sterile instruments and the adherence of strict aseptic practices. Niazi et al. (2010) demonstrated that nosocomial infections from bacteria such as *Propionibacterium acnes* and *Staphylococcus epidermidis* are likely to be associated with failures of root canal treatments.

There is a considerable body of evidence highlighting the increased accuracy of CBCT compared with periapical radiographs (Patel et al. 2009b, Paula-Silva et al. 2009b,c). All these studies compared the radiographic findings of periapical radiographs and reconstructed CBCT images to a reference standard and all concluded that CBCT had a higher degree of diagnostic accuracy compared with periapical radiographs for detecting periapical radiolucencies. The lower prevalence of pre-treatment periapical radiolucency detected by periapical radiography was most probably due to anatomical noise masking existing periapical radiolucencies (Paula-Silva et al. 2009b, Patel et al. 2009a). The reason for this improved diagnostic accuracy is principally because CBCT software creates reconstructed images from slices of data in any plane and location of the region of interest, thus eliminating lack of three-dimensional assessment and anatomical noise which hampers the accuracy of periapical radiography. This results in a higher signal-to-noise ratio and image contrast, thus improving the detection of periapical radiolucencies (Bender 1997, Soğur et al. 2009). In addition, unlike periapical radiographs that are susceptible to geometric distortion, the CBCT reconstructed images have been shown to be a very accurate representation of the region of interest (Murmulla et al. 2005, Ludlow et al. 2007, Mischkowski et al. 2007, Stratemann et al. 2008).

Well-designed prospective clinical studies are essential to determine the diagnostic outcome of root canal

treatment. The results from these studies allow us to estimate the prognosis of various treatments, thus greatly assisting the patient to make an educated informed decision on the best treatment option for their unique endodontic problem (Friedman et al. 2003, Wu et al. 2009).

The increased accuracy of CBCT may reveal periapical radiolucencies that may otherwise go undetected when assessed with conventional two dimensional radiographs. Such information may reveal different outcome predictors for endodontic treatment and also give more of an insight into the healing dynamics of periapical periodontitis (Wu et al. 2011a,b). For example, perhaps CBCT should be considered when comparing different treatment strategies (single versus multiple visit endodontic treatment, or different preparation and/or instrumentation techniques); the increased accuracy of CBCT may highlight clinically relevant differences that may otherwise not be detected with radiographs (Ng et al. 2011).

Conclusion

Diagnosis using CBCT revealed a lower healed and healing rate for primary root canal treatment than periapical radiographs. Molar teeth with no pre-operative periapical radiolucency revealed a fourteenfold higher failure rate when assessed using CBCT (17.6%) compared with periapical radiographs (1.3%).

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